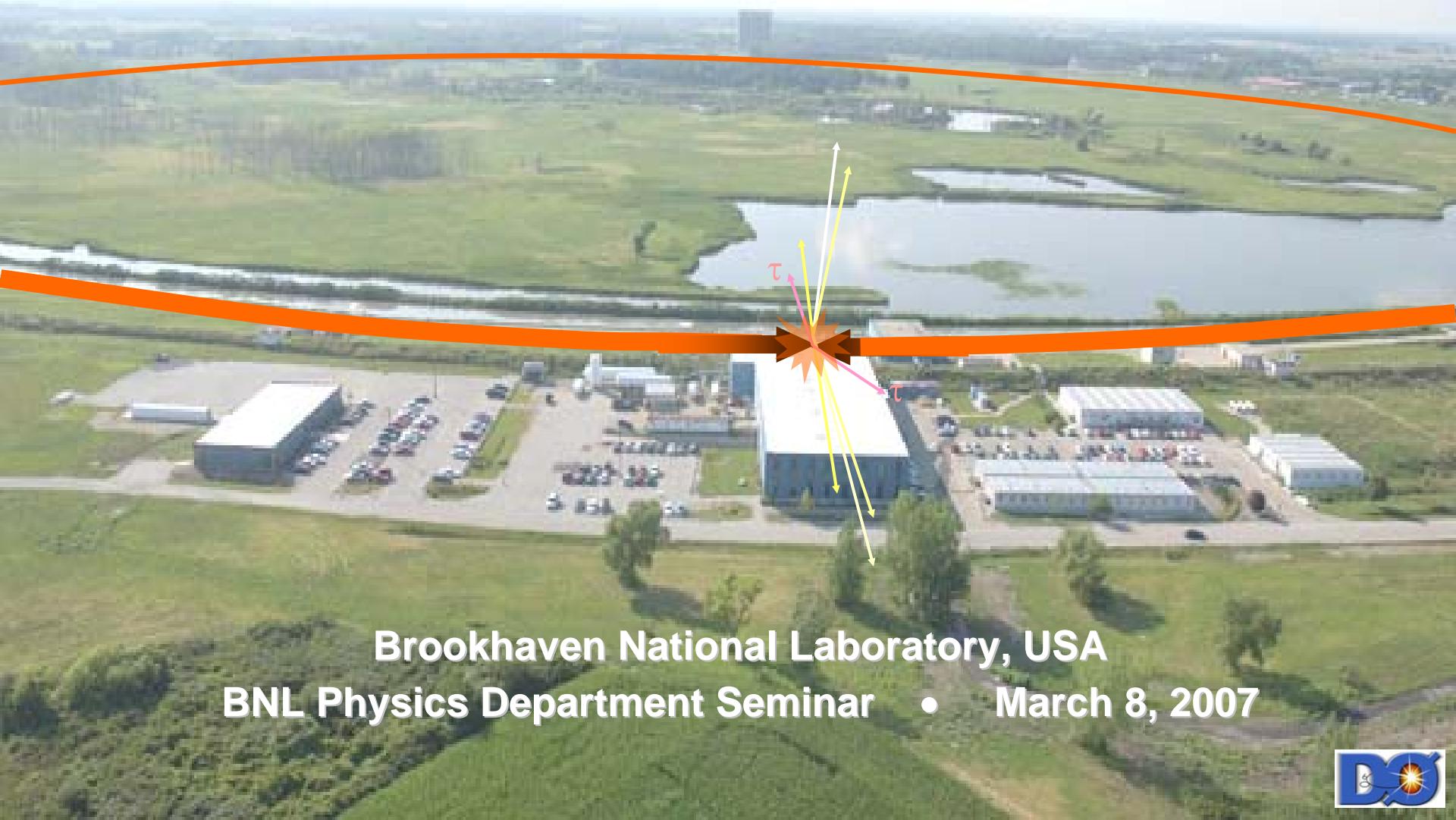


# $\tau$ -Identification and Physics with $\tau$ 's at DØ

*presented by*

**Abid Patwa**

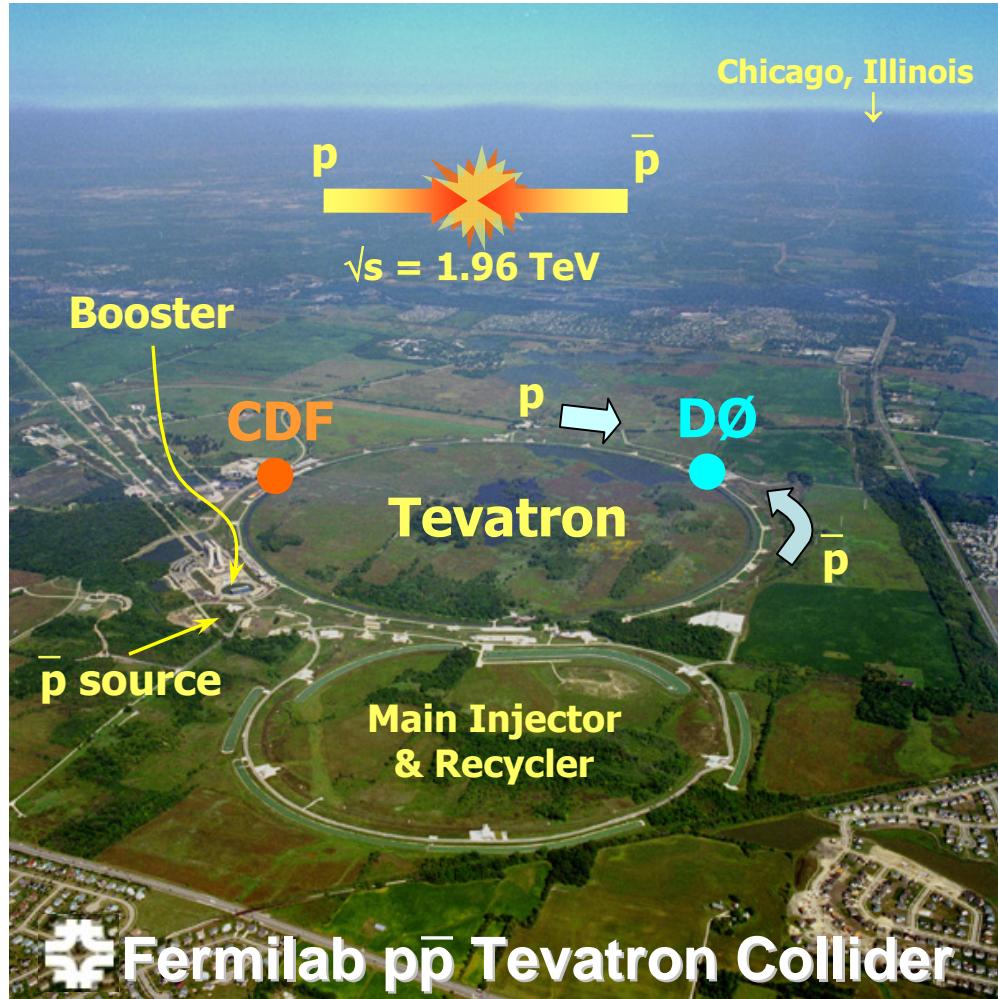


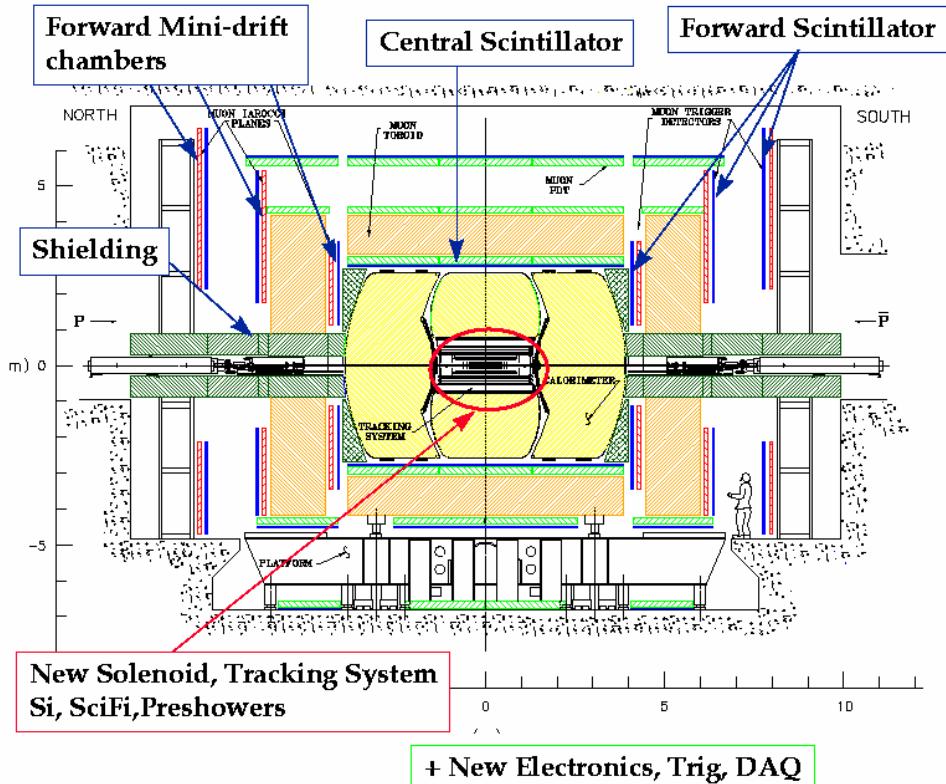
Brookhaven National Laboratory, USA

BNL Physics Department Seminar • March 8, 2007

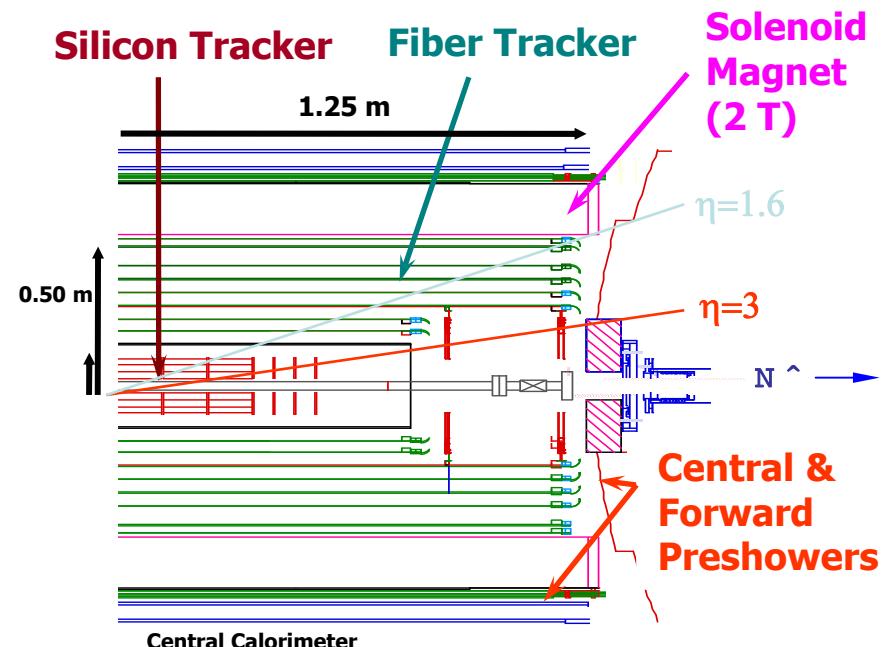
# Outline

- DØ Detector and Tevatron performance
- Motivation
- $\tau$ -identification
  - Neural Networks
- Physics studies with  $\tau$ 's
  - Electroweak: Z/W
  - $t\bar{t}$
  - Higgs
  - SUSY gaugino pair production
- Summary



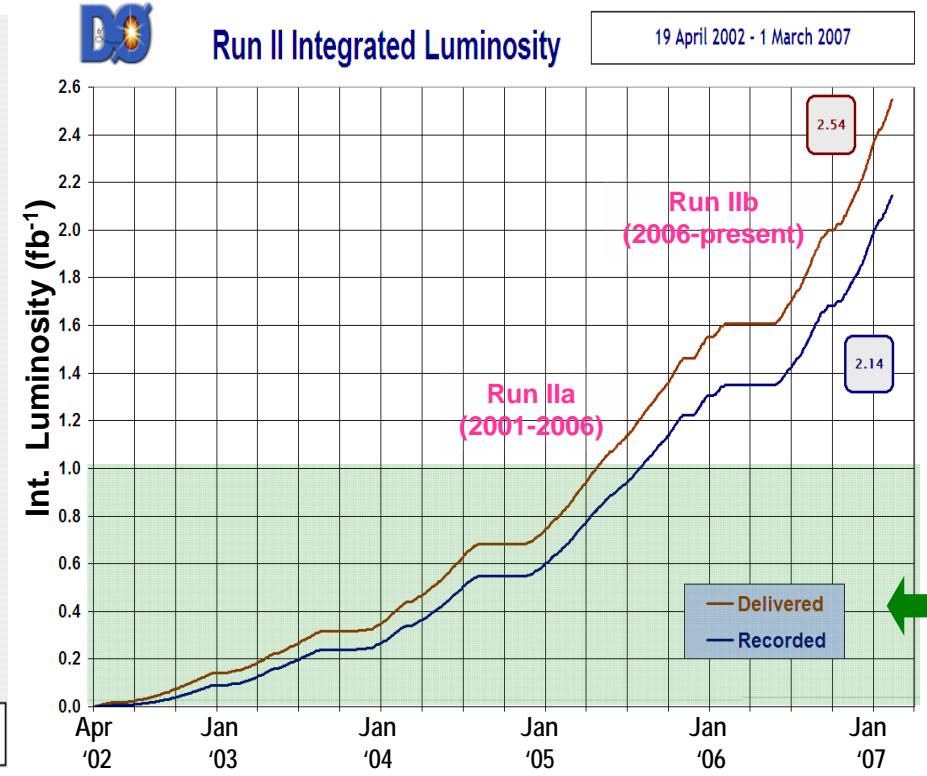
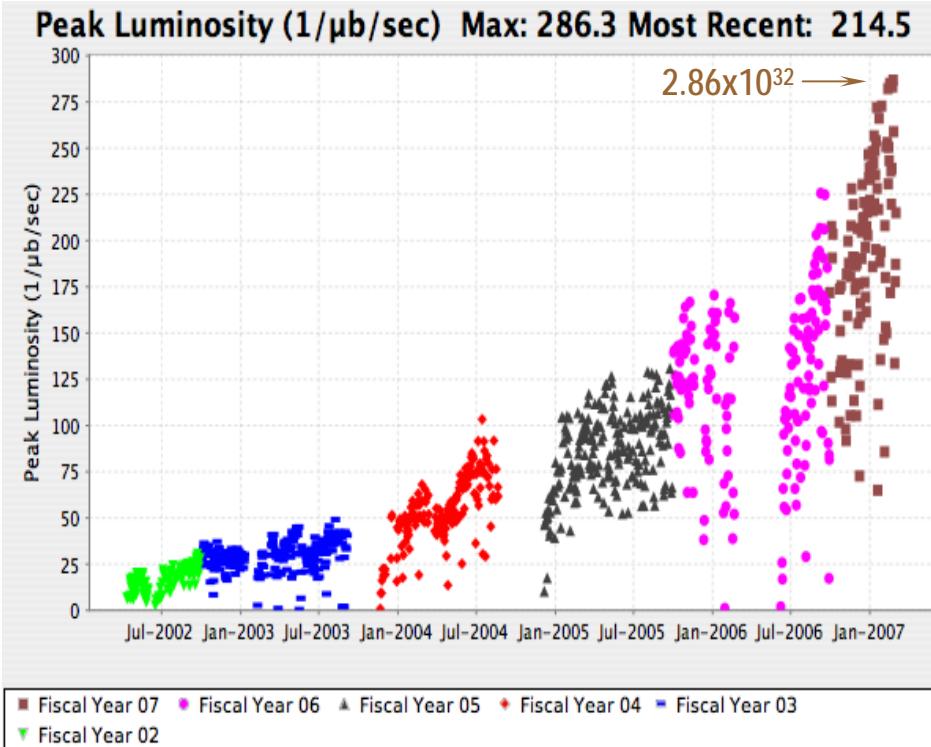


Half  $r$ - $z$  View – Inner Tracker:



- **silicon detector and scintillating fiber tracker in 2.0 T solenoidal field**
- **liquid argon/uranium calorimeters: central (CC) and two forward, end (EC) calorimeters**
- **muons: scintillators and mini-drift tubes, coverage up to  $\eta = 2.0$**

# Tevatron Performance



- Tevatron Collider and DO operating successfully in Run II
- Tevatron delivered  $\int \mathcal{L} dt \rightarrow 2.6 \text{ fb}^{-1}$ 
  - DO recorded  $> 2.1 \text{ fb}^{-1}$
  - reached peak luminosities  $> 2.8 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
  - weekly integrated luminosity  $\sim 45 \text{ pb}^{-1}/\text{week}$
  - datasets used for results reported here range from  $\sim 0.150$  to  $1 \text{ fb}^{-1}$  (Run IIa)

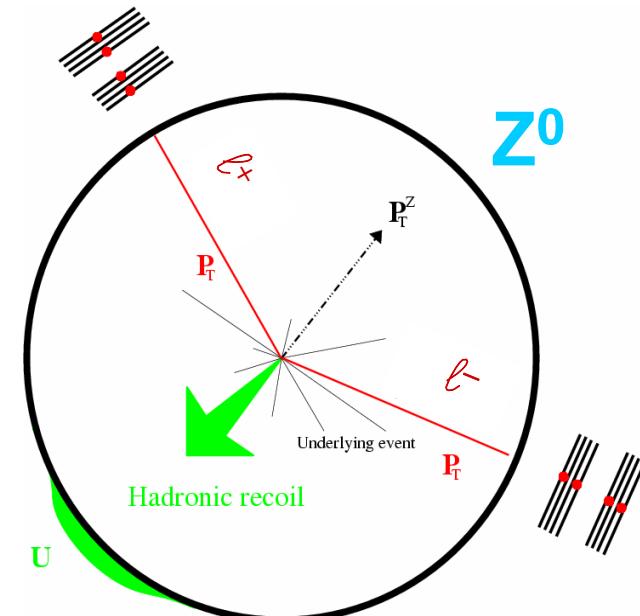
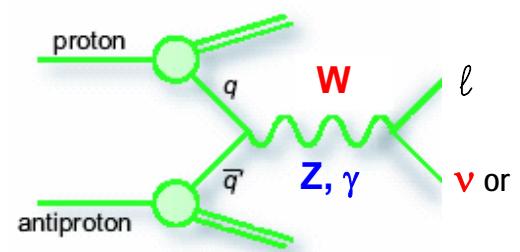
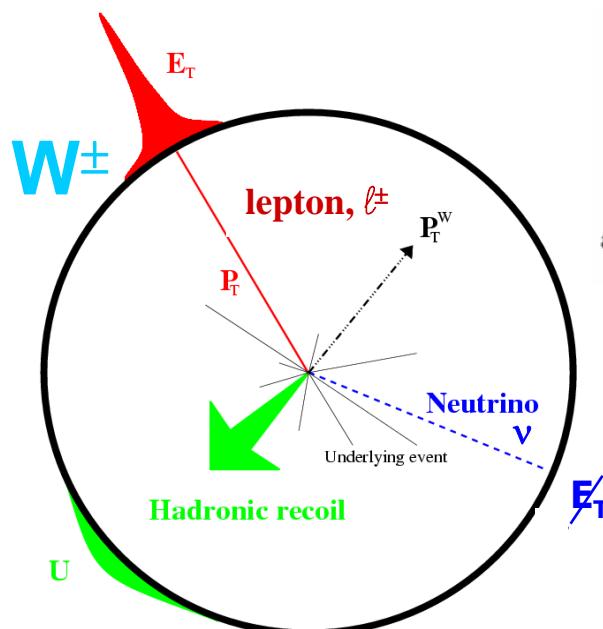


# Why study taus?

- Potentially increase acceptance for channels with leptons
  - assuming same efficiency for any lepton-ID:
    - \* single lepton channel  $\times 1.5$  increase in acceptance
    - \* di-lepton channel  $\times 2$  increase in acceptance
    - \* tri-lepton channel  $\times 3$  increase in acceptance
- Many interesting, undiscovered processes favor production of  $\tau$ 's compared to most other particles (*except nominally b-quarks*)
  - largest coupling of the SM Higgs to leptons is to  $\tau$ 's
- Minimal SUSY models with large  $\tan\beta$  favor decays to  $\tau$ 's
  - SUSY Higgs {h, H, A} cross sections and couplings to  $\tau\tau$  increase with  $\tan\beta$
  - enhanced  $H^\pm \rightarrow \tau^\pm\nu$  production due to Higgs–fermion coupling  $\propto$  fermion mass
    - \* direct search: look for excess of  $\tau$ 's in  $t\bar{t}$  events
  - $\tilde{\tau}$  decay to  $\tau + \text{LSP}$
- Important at the LHC

# W/Z: $\tau$ final states $\Rightarrow$ develop $\tau$ -ID

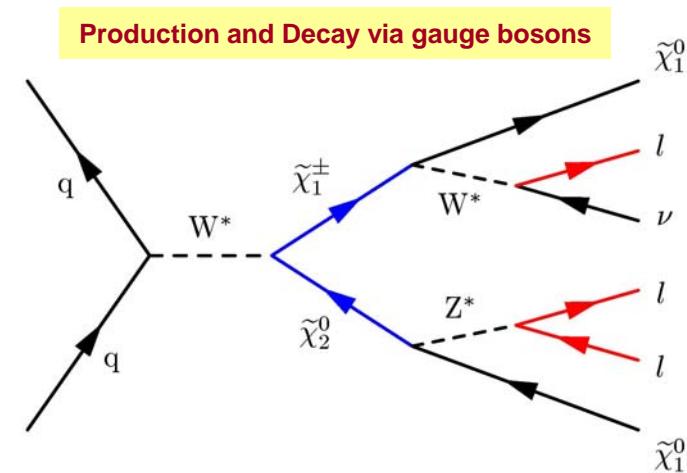
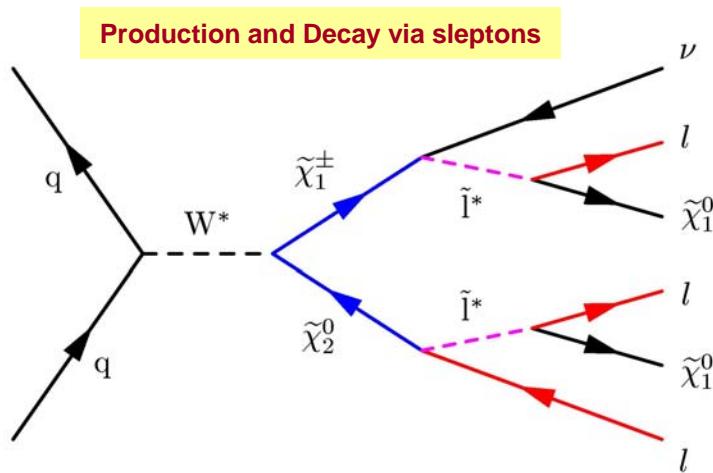
- at hadron colliders, hadronic decays of W and Z boson overwhelmed by QCD backgrounds
  - identify signature through leptonic decays  $\Rightarrow$  clean, abundant source for high  $p_T$  leptons
  - standard “candles” for measurement
- cross section measurements with  $\tau$ 's
  - test SM predictions and also help develop efficient  $\tau$ -ID algorithms



- isolated, energetic lepton
- large Missing  $E_T$  (" $E_T$ ")

- 2 isolated, energetic leptons
- leptons with opposite charge

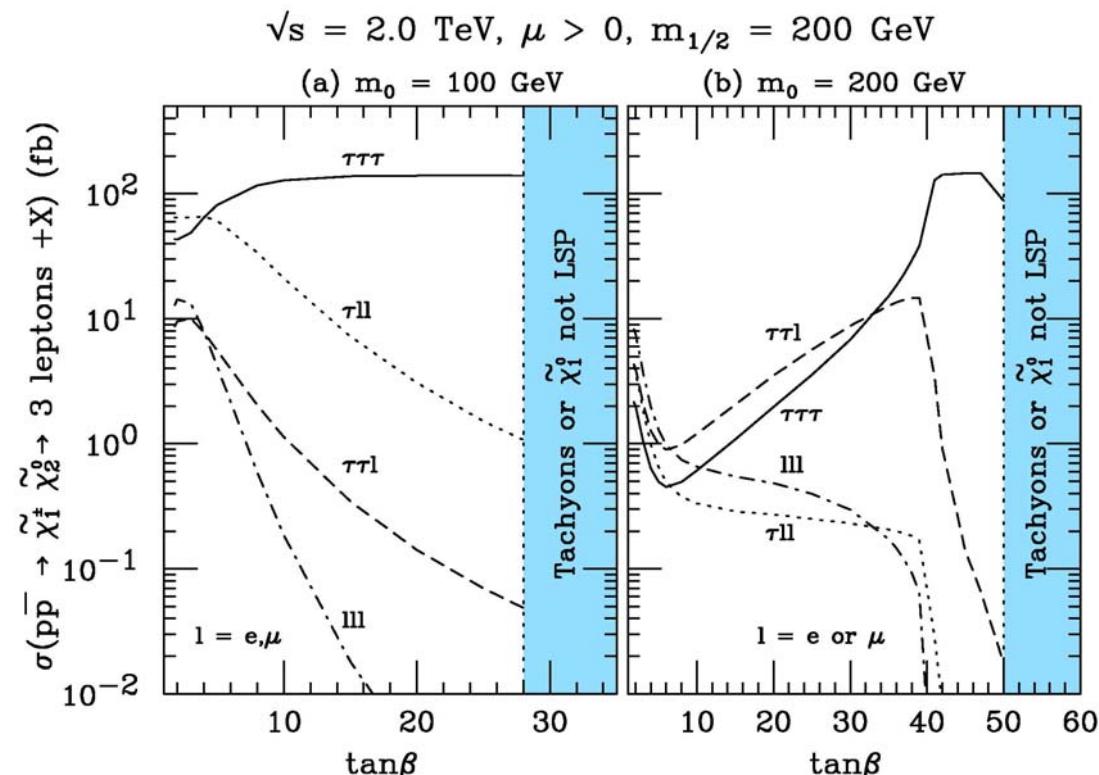
# $\tilde{\chi}\tilde{\chi}$ final states: Enhanced $\tau$ production



- In SUSY-scenarios at large  $\tan\beta$

- $m_{\tilde{\tau}} < m_{\tilde{\chi}} \Rightarrow \tilde{\chi} \rightarrow \tilde{\tau} \rightarrow \tau$
- $m_{\tilde{\tau}} < m_{\tilde{e}} \text{ or } m_{\tilde{\mu}} \Rightarrow \text{BR for final states with three } \tau\text{'s larger than } e, \mu \text{ final states}$

- trilepton +  $E_T$  channel  $\Rightarrow$  powerful study due to distinct signature





# $\tau$ properties

- Mass = 1.78 GeV
- Short lifetime,  $c\tau = 87.11 \mu\text{m}$ 
  - $\mathcal{O}(10^{-13} \text{ s})$
  - taus decay prior to reaching any detector
- Main decay channels:

$\tau$ Final State	BR (%)	Decay Type		
$e + \nu_e + \nu_\tau$	17.8	Leptonic (35.2%)	$\tau_e$	Detect with standard electron / muon ID
$\mu + \nu_\mu + \nu_\tau$	17.4		$\tau_\mu$	
$\pi(K) + \nu_\tau$	11.8	1-prong (48.7%)	$\tau_h$	Need dedicated tau ID to measure “narrow” jet objects
$\pi(K) + \nu_\tau + \geq 1 \pi^0$	36.9			
$\pi\pi\pi + \geq 0 \pi^0 + \nu_\tau$	13.9	3-prong		



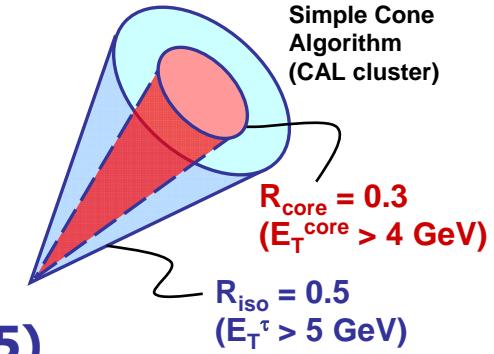
# $\tau$ triggers

- $\tau$  event selection may start with triggers designed specifically to favor  $\tau$ 's or rely on non- $\tau$  specific triggers with entire  $\tau$ -ID done offline
- Single  $\tau_h$  triggers
  - Level 1: track (isolated) and CAL tower passing jet requirement
  - Level 3: loose neural network (NN) identification based on CAL cluster
    - \* built on NN framework used offline, during physics analyses
  - used with  $E_T^{\ell}$  trigger for  $W \rightarrow \tau\nu$  analysis
- Di- $\tau$  triggers
  - may be  $\mu + \tau_h$ ,  $e + \tau_h$  or  $\tau_h + \tau_h$
  - for  $Z \rightarrow \tau_\mu \tau_h$  and  $H \rightarrow \tau_\mu, e \tau_h$ , single- $\mu$  and single- $e$  triggers can also be used
  - analyses at DØ with di- $\tau$  triggers are at early stages
- All  $\tau$  triggers add up to ~3 Hz to tape @  $10^{32}/\text{cm}^2/\text{sec}$  (max L3  $\approx$  50 Hz)

# DØ: $\tau$ reconstructed candidate

- **Begin with Calorimeter Cluster**

- Simple cone algorithm  
**(core cone size  $R = 0.3$ , isolation cone size  $R_{\text{iso}} = 0.5$ )**
  - require CAL cluster  $\text{rms} < 0.25$ 
    - \* rms = energy weighted width of cluster =  $\sqrt{\sum_{i=1}^n (\Delta\phi_i^2 E_{T_i} / E_T + \Delta\eta_i^2 E_{T_i} / E_T)}$



- **Associate EM Sub-clusters**

- Nearest Neighbor Algorithm in 3<sup>rd</sup> EM layer ( $\equiv$  shower max),  $\text{EM}_3$  cluster energy  $> 800 \text{ MeV}$
  - attach EM cells in other layers and preshower hits to the found  $\text{EM}_3$  cluster

- **Associate up to 3 tracks with  $p_T > 1.5 \text{ GeV}$  to the  $\tau$  candidate**

- track within 0.3 cone around CAL cluster
  - if more than one track, associate highest  $p_T$  track with  $\tau$  candidate
  - add 2<sup>nd</sup> (3<sup>rd</sup>) track if invariant mass calculated from tracks  $< 1.1$  (1.7) GeV and  $Q_{\text{tot}} \neq \pm 3$

# $\tau$ reconstruction

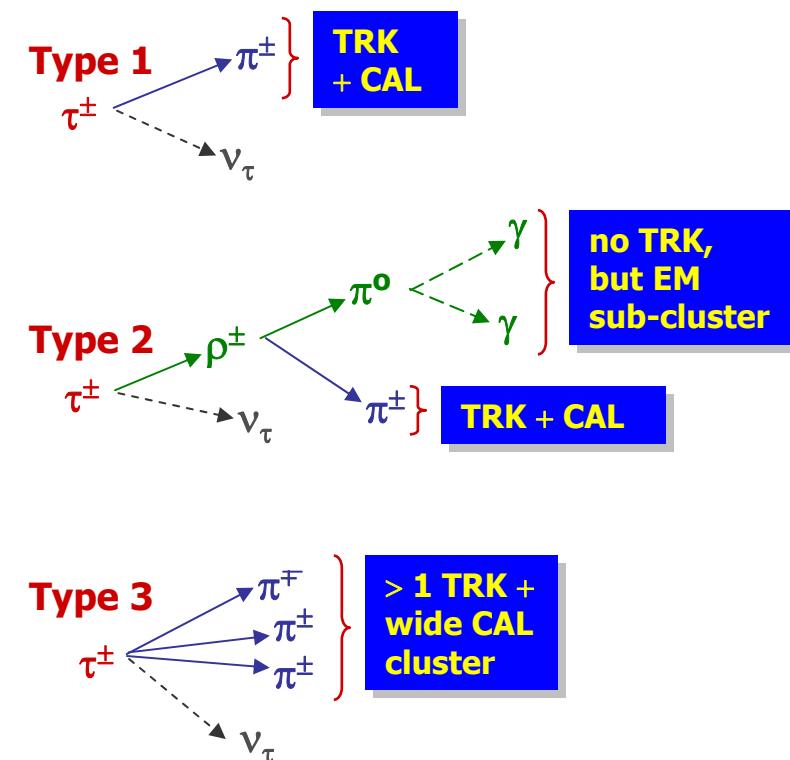
- Categorize hadronic  $\tau$  candidates into 3 types, based on their detector signature

$\tau$ -type 1 ( $\pi\nu$ -like): one track + calorimeter cluster, no EM sub-clusters

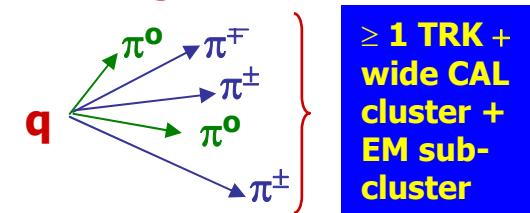
$\tau$ -type 2 ( $\rho\nu$ -like): one track + calorimeter cluster and  $> 0$  EM sub-clusters

$\tau$ -type 3 (3-prong):  $>$  one track + calorimeter cluster and  $\geq 0$  EM sub-clusters

- Reduce backgrounds from  $\tau$ 's with Neural Network (NN) techniques

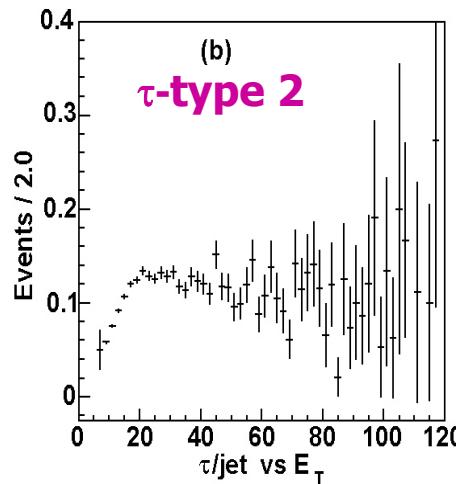
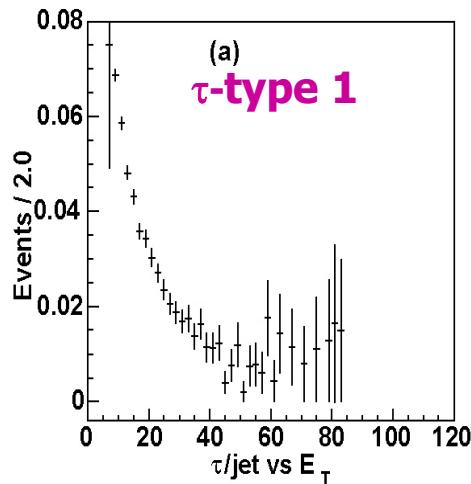


## vs. Jet-Background

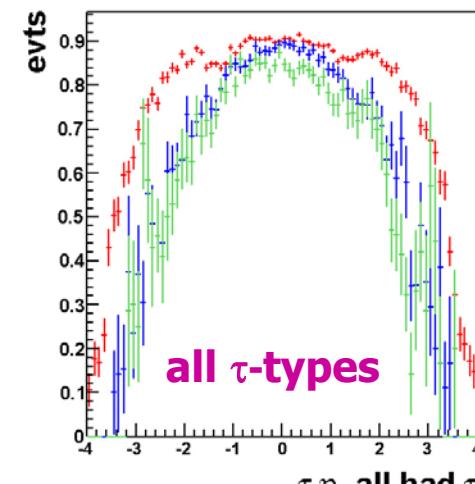
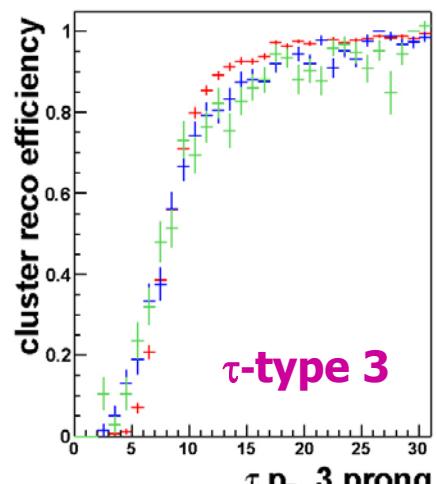
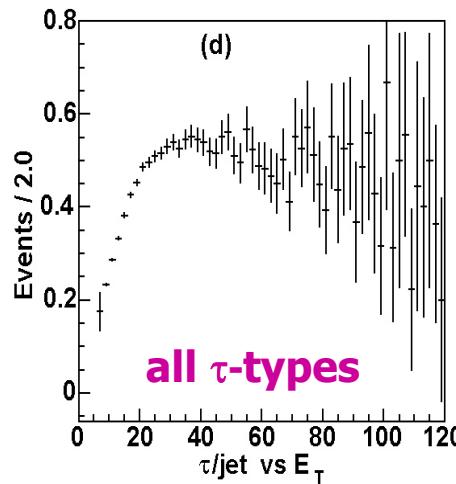
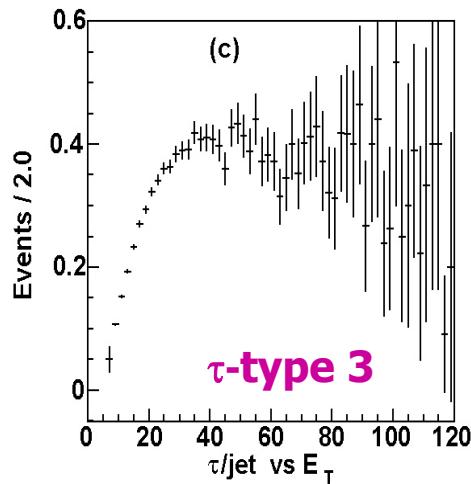
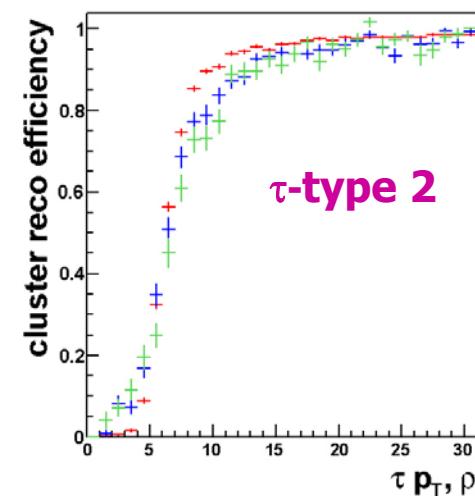
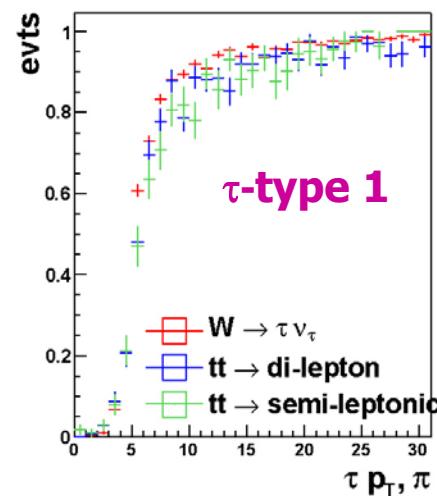


# $\tau$ candidates: Reconstruction Efficiencies

Jets faking taus (data)



Taus (MC)

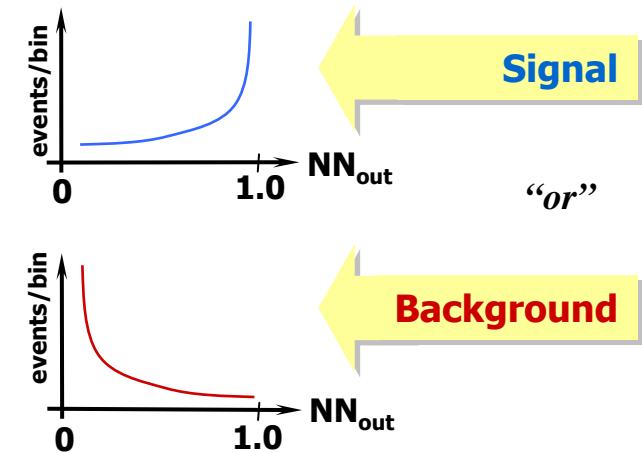
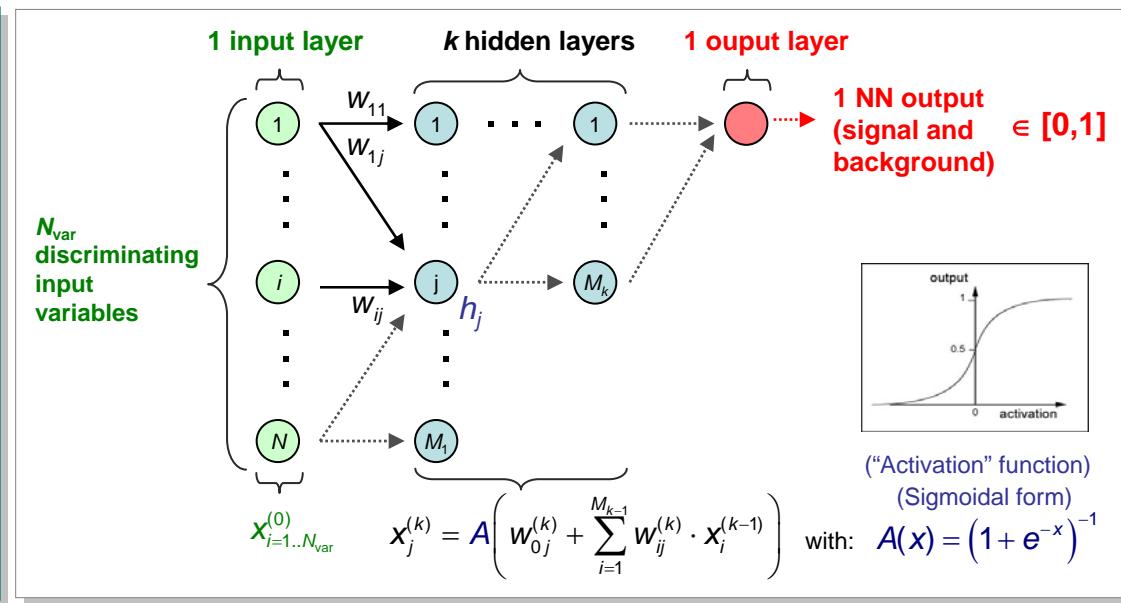


- Overall  $\tau$  reconstruction efficiency  $> 90\%$  can be achieved for  $E_T > 15 \text{ GeV}$ , but rejection of jets is low  $\Rightarrow$  depends on  $\tau$ -type and  $E_T$

# Neural Networks and $\tau$ -ID

- multivariate analysis method  $\Rightarrow$  Neural Networks (NN)
  - parallel operation with neurons (nodes) arranged in series per layer connected via links

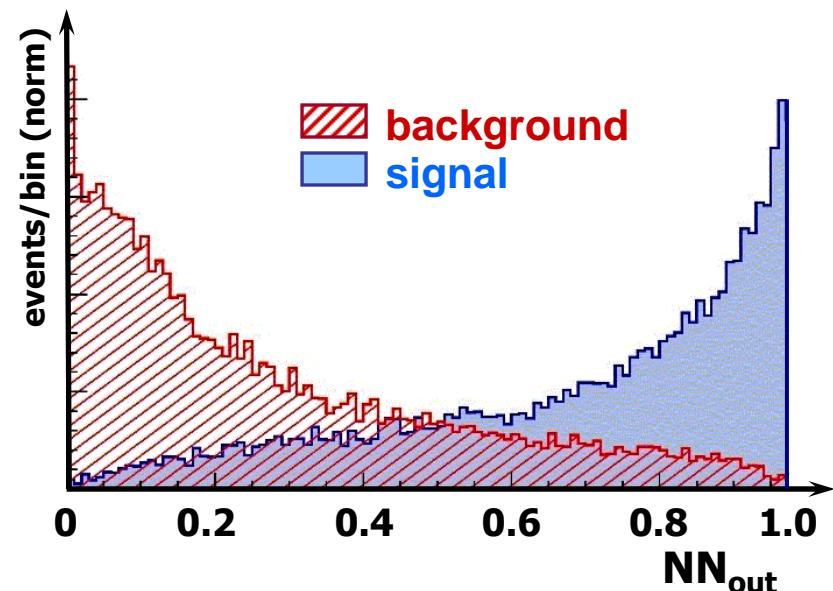
## Feed-Forward Neural Net



- input nodes, one for each measured variable ( $x_i$ )
- hidden nodes ( $h_j$ )  $\Leftrightarrow$  neuron performs a linear combination of input signals  $\sim \sum_{i=1}^{n_i} \omega_{ij} x_i$ ,  
 $x_i = i^{\text{th}}$  input
  - weights ( $\omega_{ij}$ ) for links between node  $i$  to node  $j$
- signal and background control samples
  - $\Rightarrow$  adjust weights and biases using iterative back-propagation technique (training)
  - $\Rightarrow$  optimize signal at  $NN_{\text{out}} \rightarrow 1.0$  and produce weight file (kernel)
  - $\Rightarrow$  apply kernels to  $\tau$ -physics analysis

# NN's for $\tau$ -ID (cont.)

- three separate anti-jet Neural Networks  $\Rightarrow$  one for each  $\tau$ -type
- one additional NN to reject electrons,  $NN_e$ 
  - effective in separating  $\tau$ -type 2 and electrons
- training samples for NN's:
  - signal: single  $\tau$ 's from MC (100k events, PYTHIA)
  - background:
    - \* recoiling jets in events with a non-isolated  $\mu$  from data ( $NN_{had}$ )
    - \* electrons from  $Z \rightarrow ee$  MC ( $NN_e$ )
- DO follows usual convention for NN output
  - signal:  $NN \rightarrow 1.0$
  - background:  $NN \rightarrow 0.0$
- analysis apply NN cut near 1.0 for  $\tau$ -ID





# NN input variables

- **isolation parameters:**
  - $\text{caliso} = (E_T^{\tau(R<0.5)} - E_T^{\text{core}(R<0.3)}) / E_T^{\text{core}(R<0.3)}$
  - $\text{trkiso} = \sum p_T^{\text{trk}} / \sum p_T^{\tau-\text{trk}}$ , where  $\tau\text{-trk}$  (trk) are tracks associated (unassociated) with  $\tau$  in  $R < 0.5$
  - $\text{em12isof} = (E^{\text{EM1}} + E^{\text{EM2}}) / E^\tau$ , where  $E^{\text{EM1,2}}$  are energies deposited in **1<sup>st</sup> two layers of EM calorimeter.**  
 **$\tau\text{-type 1 only.}$**
- **shower shape parameters:**
  - $\tau\text{-rms} = \sqrt{\sum_{i=1}^n (\Delta\phi_i^2 E_{T_i} / E_T + \Delta\eta_i^2 E_{T_i} / E_T)}$
  - **$EM$  fractions**, fraction of  $E_T$  in EM calorimeter.  **$\tau\text{-types 2 and 3.}$**
  - **$hadronic$  fractions**, fraction of  $E_T$  in hadronic cal.  **$\tau\text{-types 1 and 2.}$**
  - $\text{profile} = (E_T^{\text{tower1}} + E_T^{\text{tower2}}) / E_T^\tau$ , where  $E_T^{\text{tower1,2}}$  are  $E_T$  of two most energetic calorimeter towers
  - $\text{EMprofile} = E_T^{\text{leadingEM-subcluster}} / E_T^{EM_3}$



# NN input variables (cont.)

- and build correlations between CAL and track:

- $E_T^\tau / (E_T^\tau + \sum p_T^{\tau-trks})$ , **τ-types 2 and 3.**

- $\delta\alpha$  = angle between  $\sum \tau-tracks$  and  $\sum EM-subclusters$ , **Used for τ-types 2 and 3.**

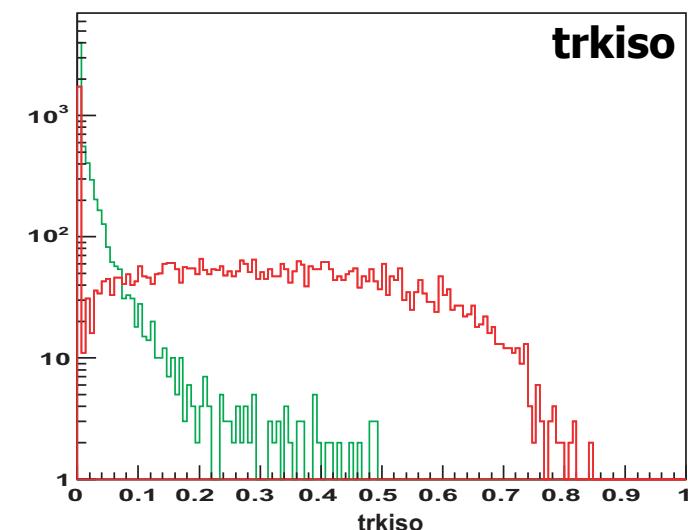
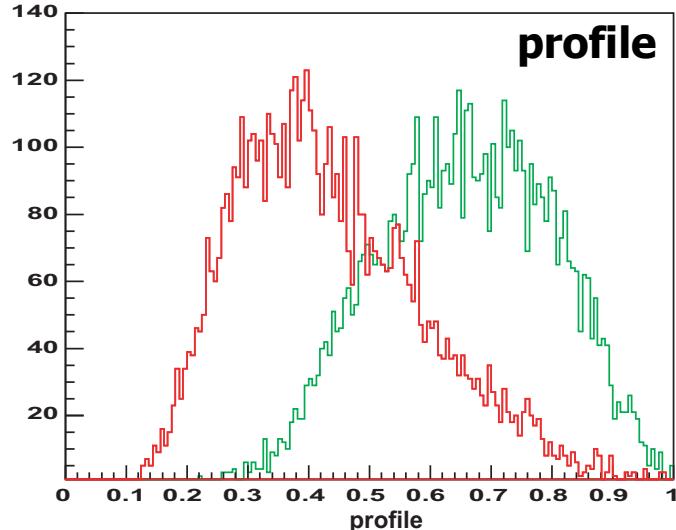
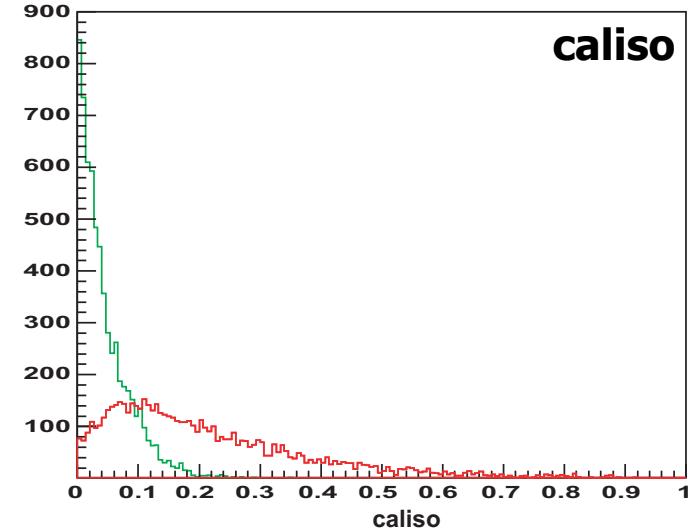
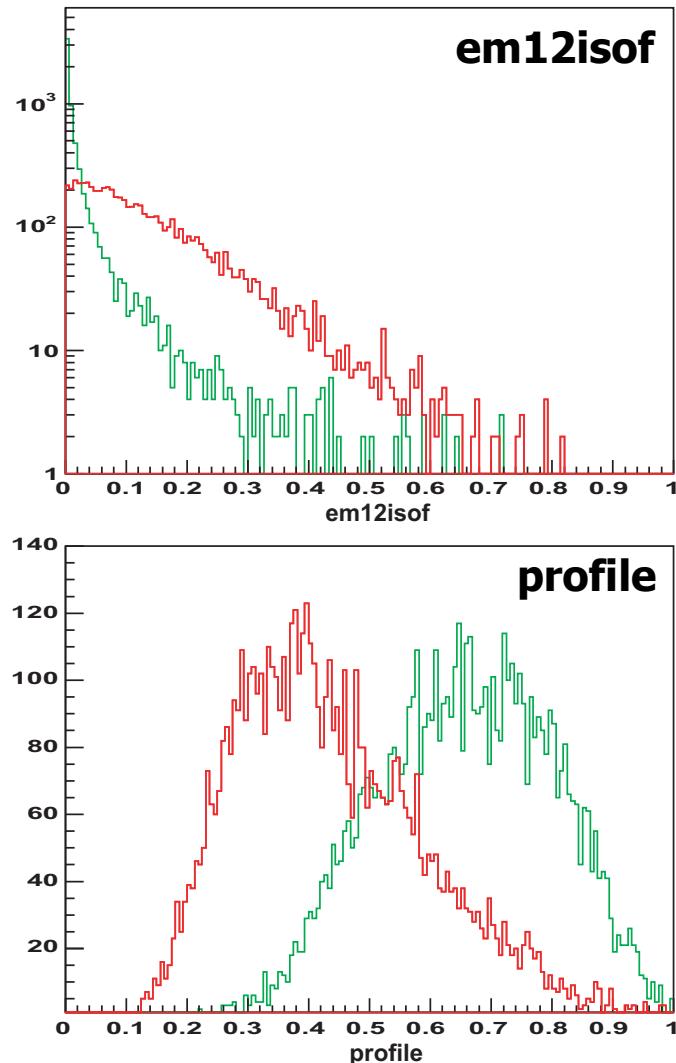
in general, most NN input variables are ratios of track  $p_T$  and calorimeter energies that have different distributions for  $\tau$ -signal and jet backgrounds

AND

their use in NN per  $\tau$ -type is optimized during NN training

# a few example NN input variables...

**Signal (MC  $\tau$ ) and Background (jets from data) for  $\tau$ -type 1**



- One distribution alone may not be able to clearly separate signal from background  $\Rightarrow$  effective when applied together within a NN

# Jet- $\tau$ discrimination

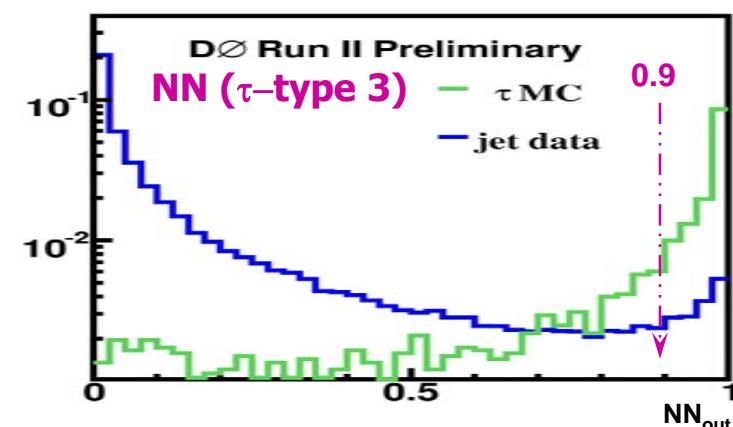
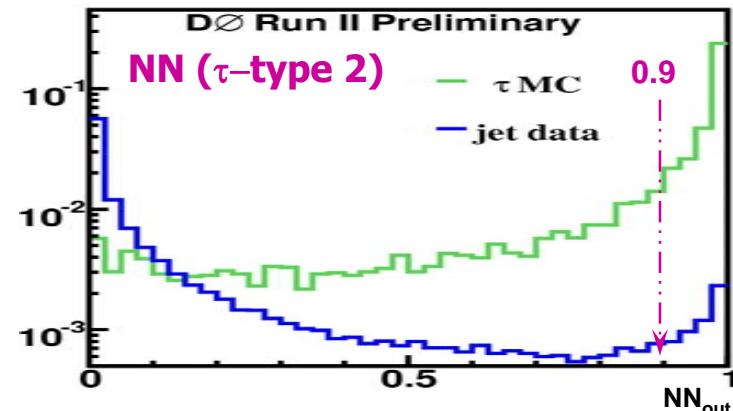
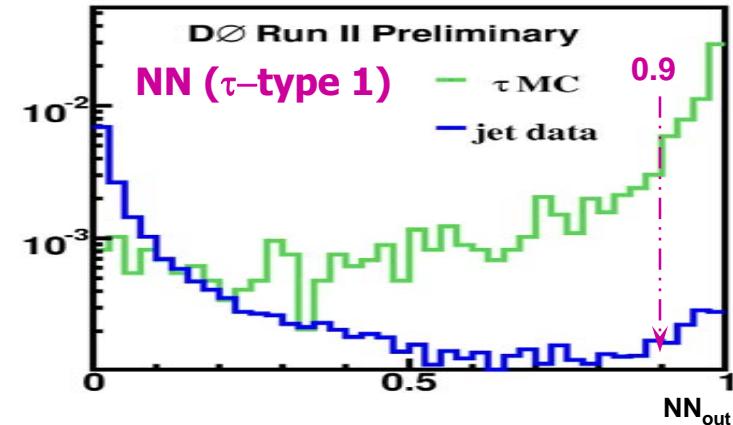
- apply NN to separate QCD jets from  $\tau$ 's

**Efficiencies (%)**

$20 < E_T^\tau < 40 \text{ GeV}, |\eta^\tau| < 2.5$

$\tau$ -type	1	2	3	all
Jets	2	12	38	52
$\tau$	11	60	24	95
<b>NN &gt; 0.9</b>				
Jets	0.06	0.24	0.80	1.1
$\tau$	7	44	16	67

- NN > 0.9 reduces jet background by  $\times \sim 50$  while keeping total  $\tau$  efficiency near 70%
- if exclude  $\tau$ -type 3  $\Rightarrow \times \sim 3$  increase in S/B, with only 16% loss in efficiency



# e- $\tau$ discrimination

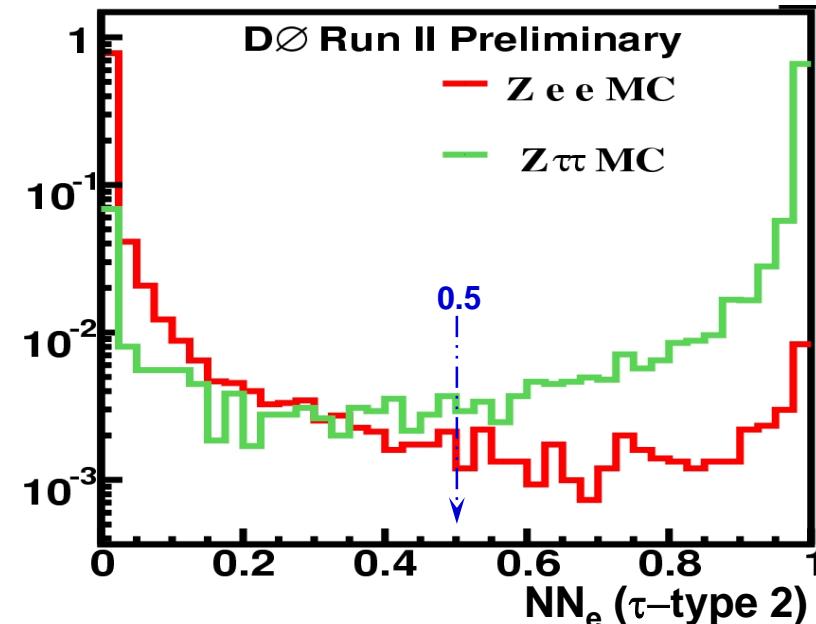
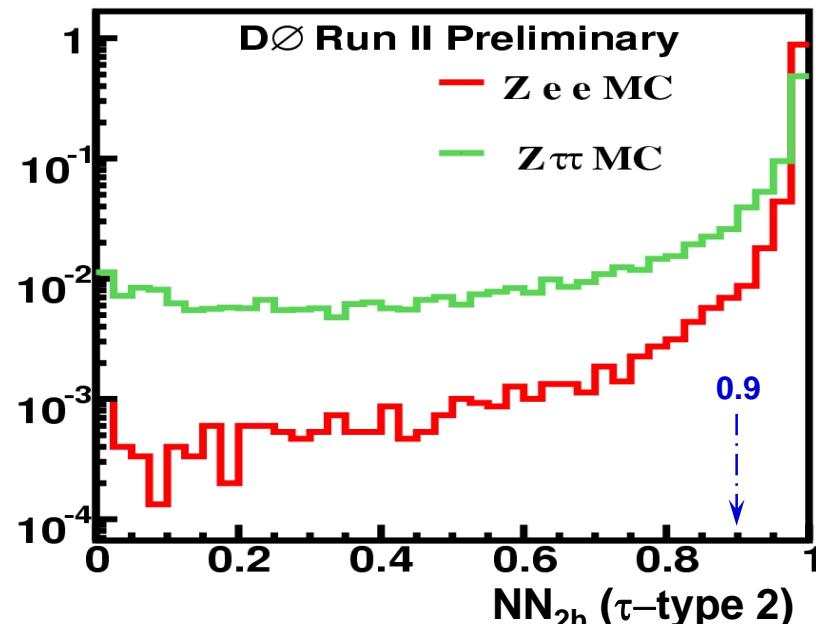
- electrons make nice type-2  $\tau$  candidates
  - cannot effectively be separated using  $NN_{had}$
- $NN_e$  trained with electrons ( $Z \rightarrow ee$ ) as backgrounds
  - apply  $NN_{had}$  ( $\equiv NN_{2h}$ ) to discriminate  $\tau$ 's from jets
  - apply  $NN_e$  to discriminate electrons from  $\tau$ 's

## Efficiencies (%)

$20 < E_T^\tau < 40 \text{ GeV}, |\eta^\tau| < 2.5$

	$NN_{2h} > 0.9$	$NN_e > 0.5$
e	98	3.4
$\tau$	44	38

- 98% electrons can pass with  $NN_{2h} > 0.9$
- loose  $NN_e$  cut reduces e's to 3.4% with only 6% loss in  $\tau$  efficiency



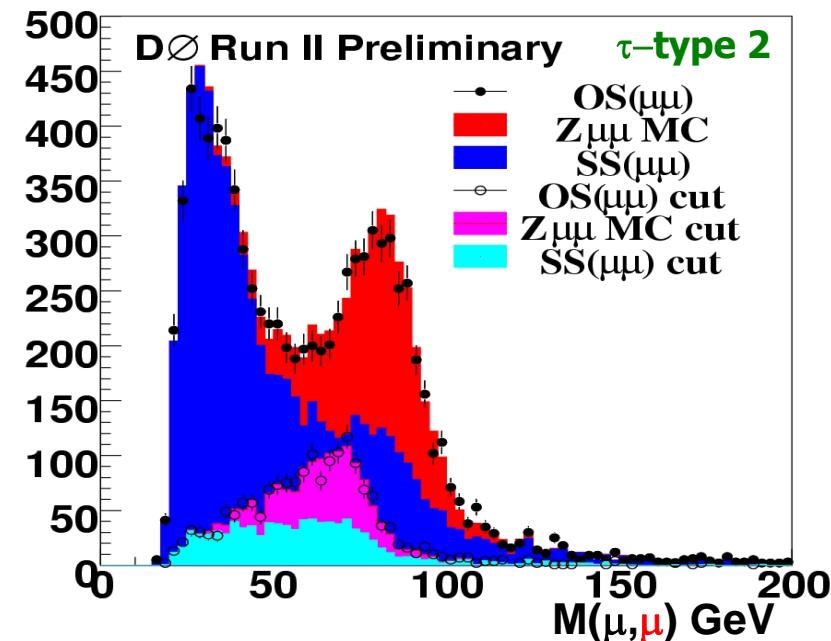
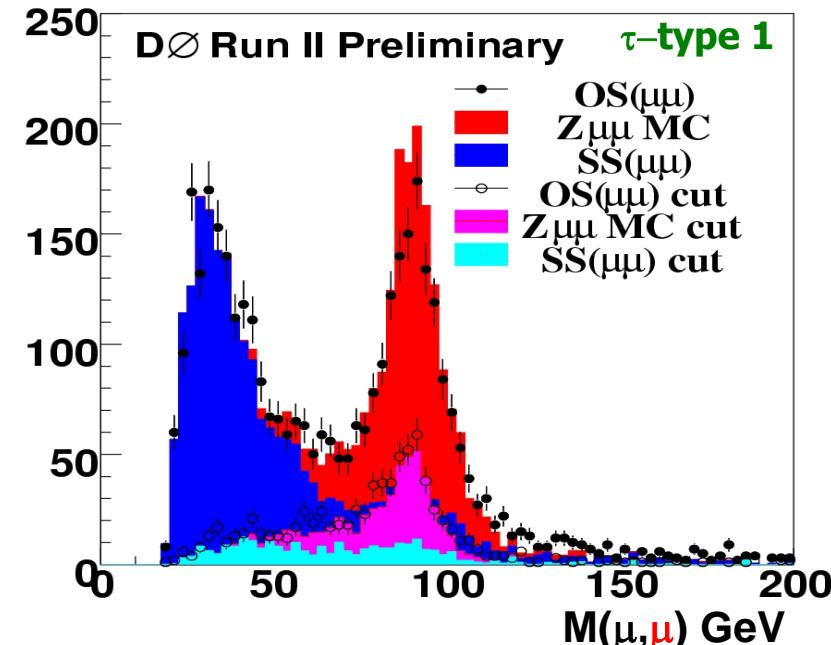
# $\mu$ - $\tau$ discrimination

- NN trained on jets and  $\tau$ 's cannot separate misidentified  $\mu$ 's
- use longitudinal shape variable

$$\mathcal{R}_\mu = (E_T^\tau - E_{55CH}^{trk}) / p_T^{trk}$$

where  $E_{55CH}^{trk}$  = energy in the Coarse Hadronic (CH) layers of calorimeter (5  $\times$  5 towers) around  $\tau$ -track

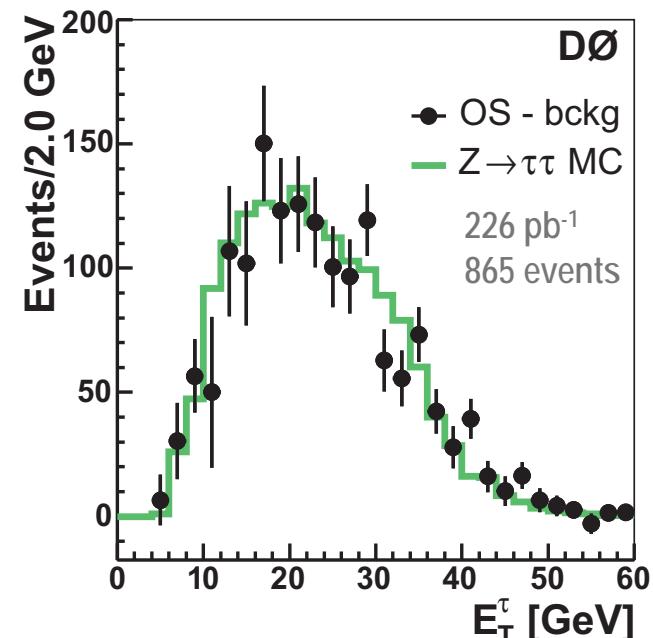
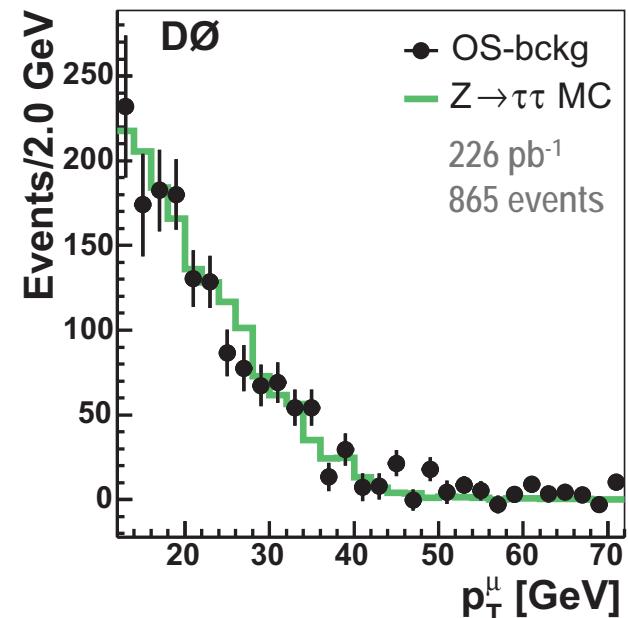
- $\mu \equiv$  misidentified as  $\tau$  tend to populate and peak at low values of  $\mathcal{R}_\mu$  than for real  $\tau$  leptons
  - $\mathcal{R}_\mu > 0.7$  tends to suppress  $\mu$  and  $\tau$ 's matched to  $\mu$ 's





# $Z \rightarrow \tau_\mu \tau_{h,e}$ Cross Section

- consider channel  $\tau_1 \rightarrow \mu$  and  $\tau_2 \rightarrow \text{had or } e$
- events selected with single  $\mu$  trigger
- $\int \mathcal{L} dt \rightarrow 226 \text{ pb}^{-1}$
- optimized offline selections
  - $p_T^\mu > 12 \text{ GeV}; |\eta^\mu| < 2.0$
  - $E_T^\tau > 10 (5) \text{ GeV}$  for  $\tau$ -types 1, 3 (2);  $|\eta^\tau| < 3.0$
  - select back-to-back  $\mu\tau$  pairs ( $|\phi_\mu - \phi_\tau| > 2.5$ )
- significant background sources (other than QCD)
  - $W \rightarrow \mu\nu + \text{jets}$ :  $\mu$  plus a jet misidentified as  $\tau$
  - $Z/\gamma^* \rightarrow \mu\mu$ :  $\mu$  mis-measured as  $\tau_{\text{had}}$ 
    - \*  $\mathcal{R}_\mu > 0.7 \Rightarrow$  suppresses 70%  $\mu^+\mu^-$  background while keeping 98% signal
- split  $\mu\tau$  data sample into opposite sign (OS) and same sign (SS)
  - OS  $\Rightarrow$  signal and SS  $\Rightarrow$  estimate QCD background in signal sample





# $Z \rightarrow \tau_\mu \tau_{h,e}$ Backgrounds and Systematics

Predicted and Observed Contributions to OS events ( $\Sigma \tau$ -types, $NN > 0.8$ )	
<b>QCD</b>	<b><math>984 \pm 46</math></b>
$Z/\gamma^* \rightarrow \mu\mu$	<b><math>70 \pm 16</math></b>
$W \rightarrow \mu\nu$	<b><math>58 \pm 20</math></b>
$Z/\gamma^* \rightarrow \tau\tau$	<b><math>914 \pm 24</math></b>
<b>Total</b>	<b><math>2026 \pm 57</math></b>
<b>OS events</b>	<b>2008</b>

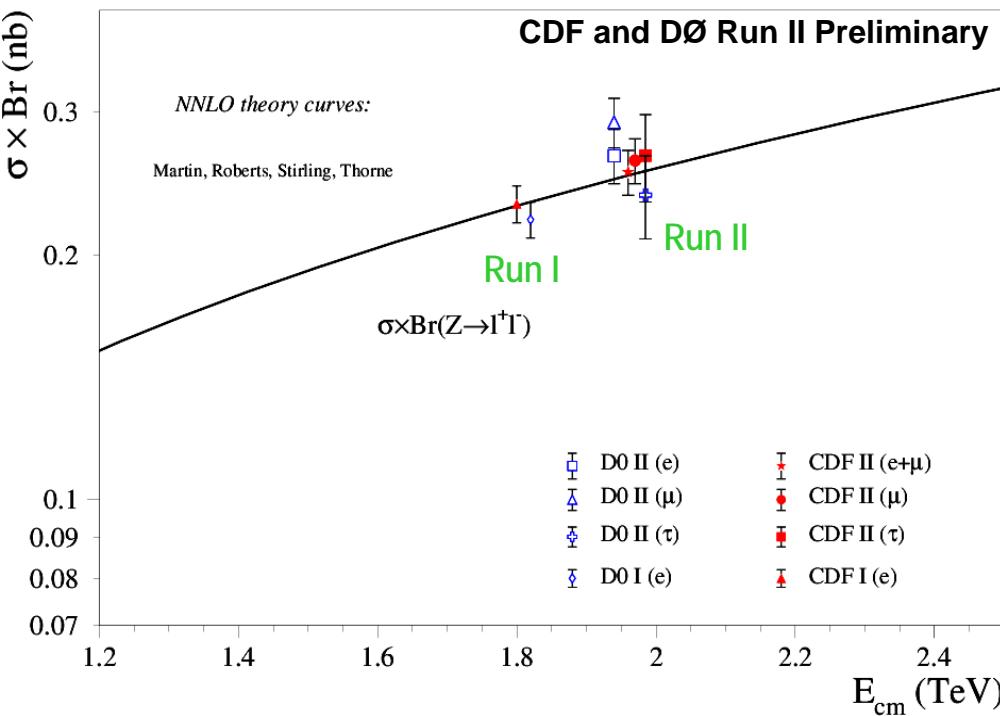
$\int \mathcal{L} dt = 226 \text{ pb}^{-1}$ : 2008 **OS events with  $NN > 0.8$** ;  
 $\text{QCD} \sim 48\%$ ,  $W \rightarrow \mu\nu + Z \rightarrow \mu\mu \sim 6\%$

- **main systematics:**
  - **energy scale** ~ 2.5%
  - **determining background contributions** ~ 4-5%
  - **$\tau$  lepton-ID** ~ 3-4%
  - **PDF (CTEQ6)** ~ 1.7%

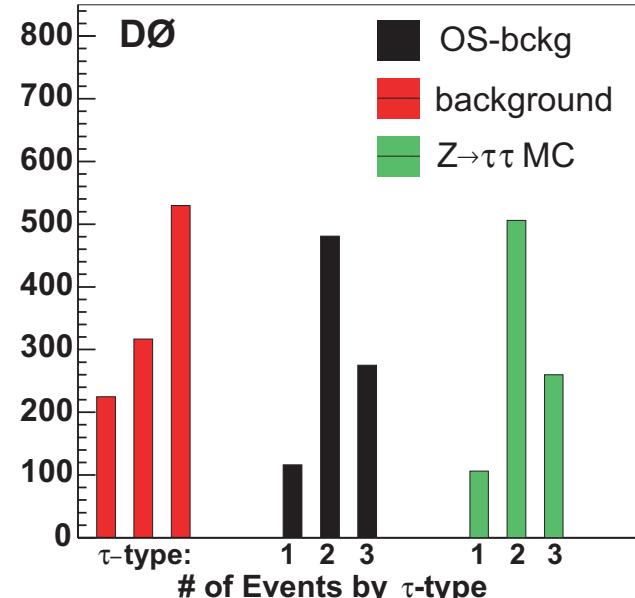
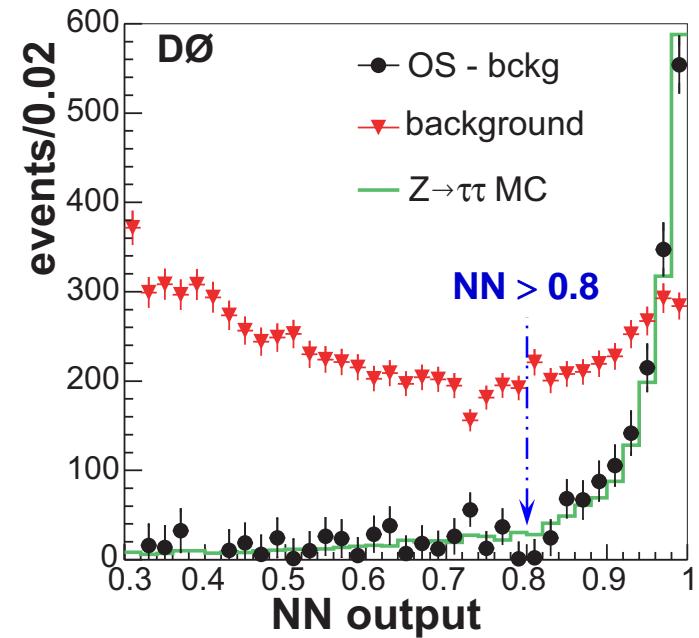


# $Z \rightarrow \tau_\mu \tau_{h,e}$ Cross Section: PRD

- distributions of OS data – background in good agreement with  $Z \rightarrow \tau\tau$  MC
- $\sigma \times \text{BR} \Rightarrow$  consistent and in good agreement with NNLO theoretical calculations



$\sigma(p\bar{p} \rightarrow Z) \times \text{BR}(Z \rightarrow \tau\tau) =$   
 $237 \pm 15 \text{ (stat)} \pm 18 \text{ (sys)} \pm 15 \text{ (lum)} \text{ pb}$   
**PRD 71, 072004 (2005)**  
[Theory:  $242 \pm 9 \text{ pb}$ ]

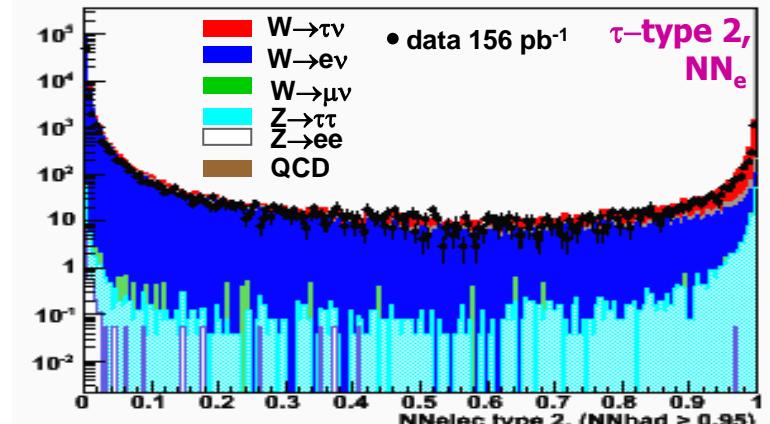
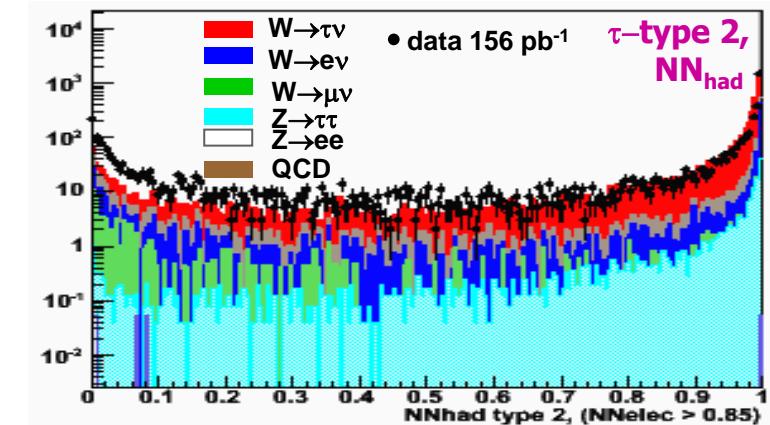
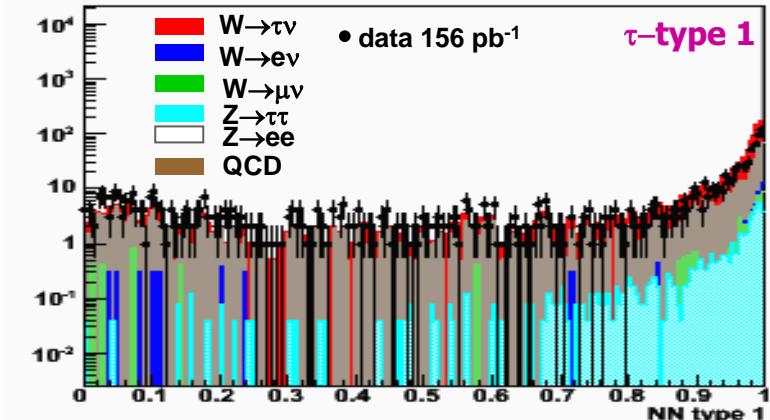


# $W \rightarrow \tau\nu$ Studies

- Use  $E_T (> 20 \text{ GeV})$  plus jet ( $E_T > 7 \text{ GeV}$ ) with isolated track ( $p_T > 10 \text{ GeV}$ ) triggers
  - $\int \mathcal{L} dt = 156.4 \text{ pb}^{-1}$

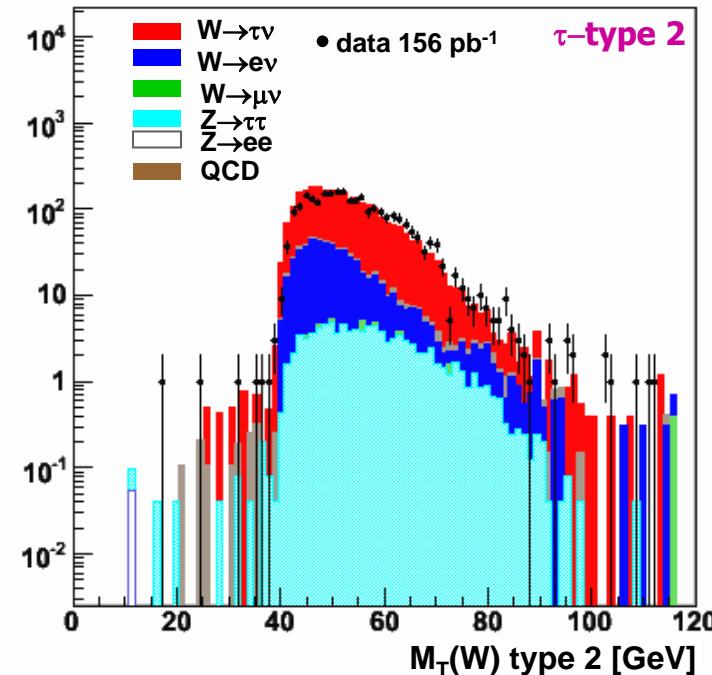
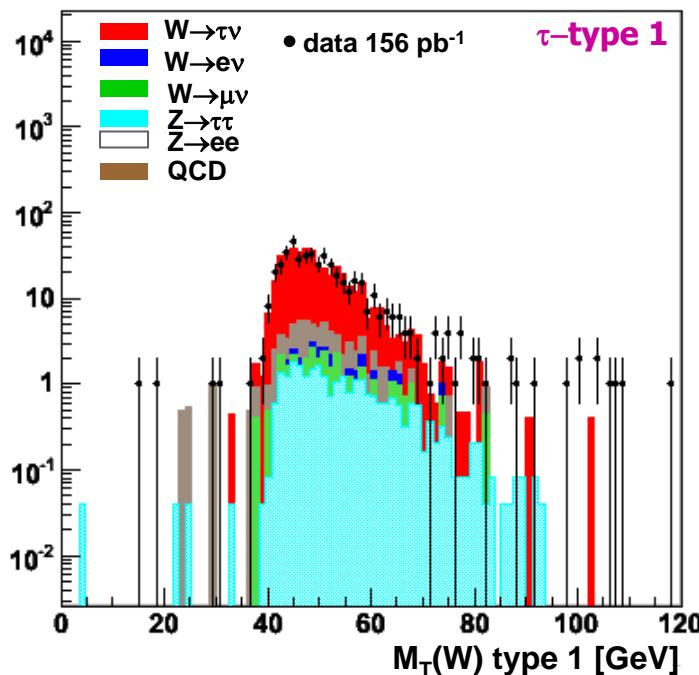
Offline Selections	$\tau$ -types
0 or mono-jets; if $\geq 2$ jets, veto jets $p_T > 15 \text{ GeV}$	1, 2
$E_T^\tau > 20 \text{ GeV}$	1, 2
$p_T^{\text{trk}} > 20 \text{ (15) GeV}$	1, (2)
$\eta < 1.0$	1, 2
$E_T > 20 \text{ GeV}$	1,2
veto events with good e or good $\mu$	–
$NN_e > 0.85$	2
$NN_{\text{had}} > 0.95$	1, 2

- QCD background estimated from data using back-to-back di-jet sample
  - tag high-quality jet and probe for  $\tau$ 's on the other side
- $\tau$ -type 1 dominated by QCD
- $\tau$ -type 2 dominated by electrons



# Transverse W-mass

- studies still in progress...
- systematic uncertainties being understood

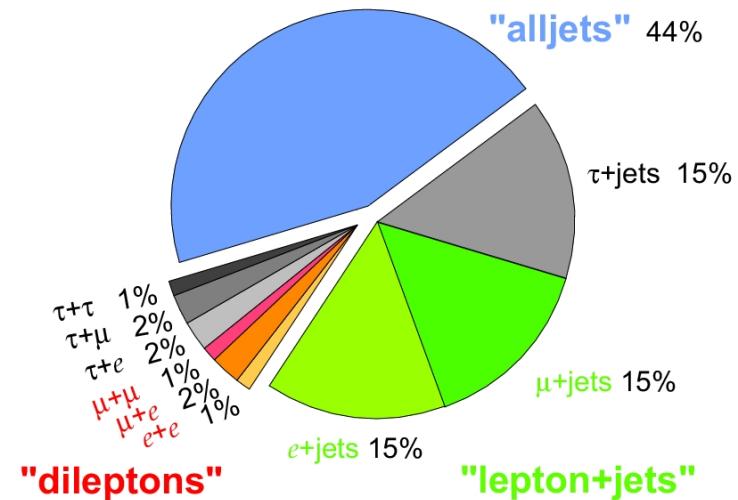
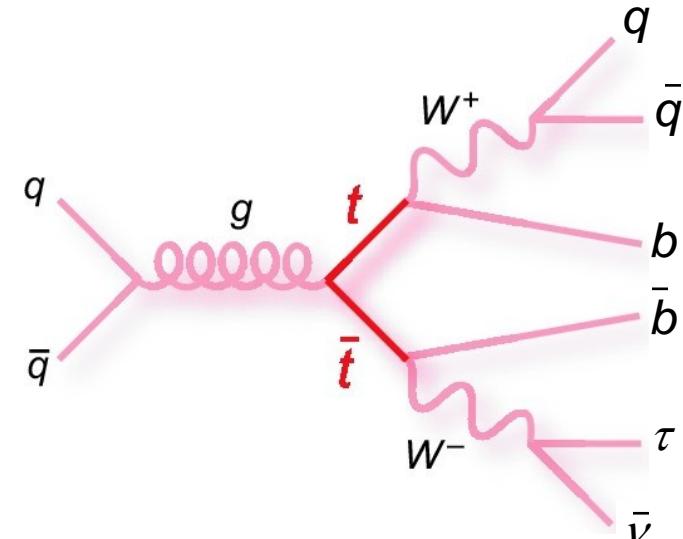


- after NN cuts, preliminary yields:

$\tau\text{-types:}$	1	2
QCD	60	102
EW-backgrounds	43	567
signal (data)	374	1941

# $t\bar{t} \rightarrow \tau + \text{jets}$

- $\tau + \text{jets}$  decay mode contributes 15% of  $t\bar{t}$  production
  - same as  $e + \text{jets}$ ,  $\mu + \text{jets}$
- $\tau \rightarrow e$  or  $\tau \rightarrow \mu$  difficult to distinguish from prompt (primary) ones at hadron collider
  - DØ considers only  $\tau \rightarrow \text{had}$
  - i.e., accounts for 65% of  $\tau$ -lepton BR
- signal contains high (> 3) number of jets and sizeable (> 15 GeV)  $E_T$
- two dominant backgrounds:
  - QCD: jets faking  $\tau$ 's or fake or real b-jets  $\Rightarrow$  estimated from data
  - $W + \text{jjjj}$  where  $W \rightarrow \tau, \mu, \text{ or } e + \nu$ : real or fake  $\tau$ 's or b-jets  $\Rightarrow$  estimated from MC
- $Zb\bar{b}$  background where  $Z \rightarrow \tau\tau$ : real  $\tau$  and real b-jets possible but negligible



**DØ: first measurement of  $t\bar{t}$  cross section in this  $\tau$ -decay channel**

# $t\bar{t} \rightarrow \tau + \text{jets}$ : Event Selection

- Data collected using 4-jet trigger with  $\int \mathcal{L} dt \rightarrow 349 \text{ pb}^{-1}$

## Stage 1 - Pre-selection:

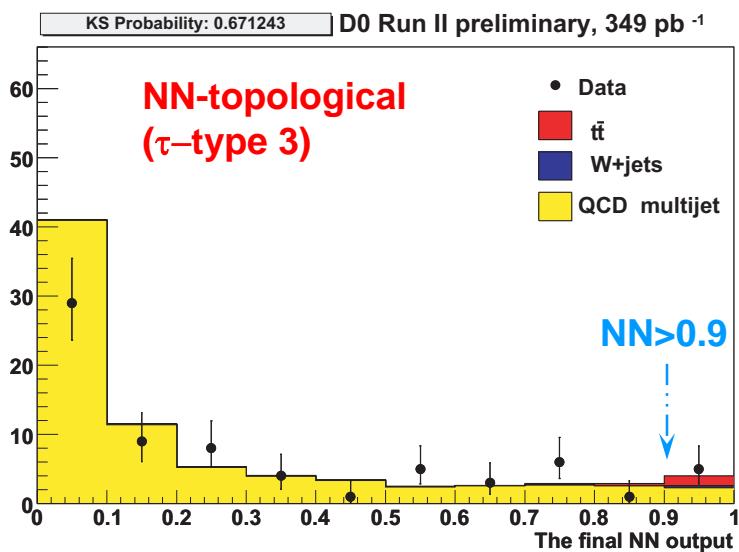
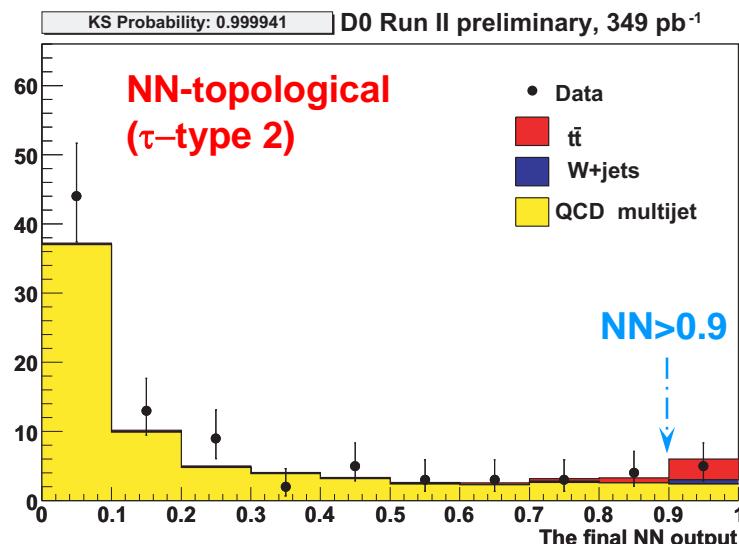
- at least 4 jets with  $p_T > 20 \text{ GeV}$
- $E_T$  significance  $> 3$
- no isolated  $\mu$  or  $e$

## Stage 2 - ID Selections:

- one  $\tau$  (types 2, 3) candidate with  $NN > 0.95$
- at least one tagged b jet

## Stage 3 – Kinematic and Topological variable NN (reduce QCD and W+jets background):

- Aplanarity and Sphericity: eigenvalues of Momentum Tensor of jets
  - higher for  $t\bar{t}$  events than QCD
- $H_T$ : sum of jets and  $\tau p_T$
- Centrality:  $H_T/H_E$ , where  $H_E = \sum \text{jet energies}$
- Top and W mass likelihood
  - $\chi^2$  variable
- Lifetime and  $p_T$  of b-tagged jet





# $\sigma(t\bar{t})$ : Measurement

final cut:  $NN_{\text{topological}} > 0.9$

$\tau + \text{jets}:$	$\tau\text{-type 2}$	$\tau\text{-type 3}$
$N_{\text{obs}}$	5	5
QCD	$2.41 \pm 0.09$	$2.33 \pm 0.09$
W + jets	$0.60 \pm 0.03$	$0.27 \pm 0.01$
S (7 pb)	$3.83^{+0.46}_{-0.51}$	$1.80^{+0.22}_{-0.23}$
s + b	$6.84^{+0.46}_{-0.51}$	$4.39^{+0.22}_{-0.23}$

- for  $\tau\text{-type 2}$ :

$$3.63^{+4.72}_{-3.50} (\text{stat})^{+0.49}_{-0.48} (\text{syst}) \pm 0.24 (\text{lum})$$

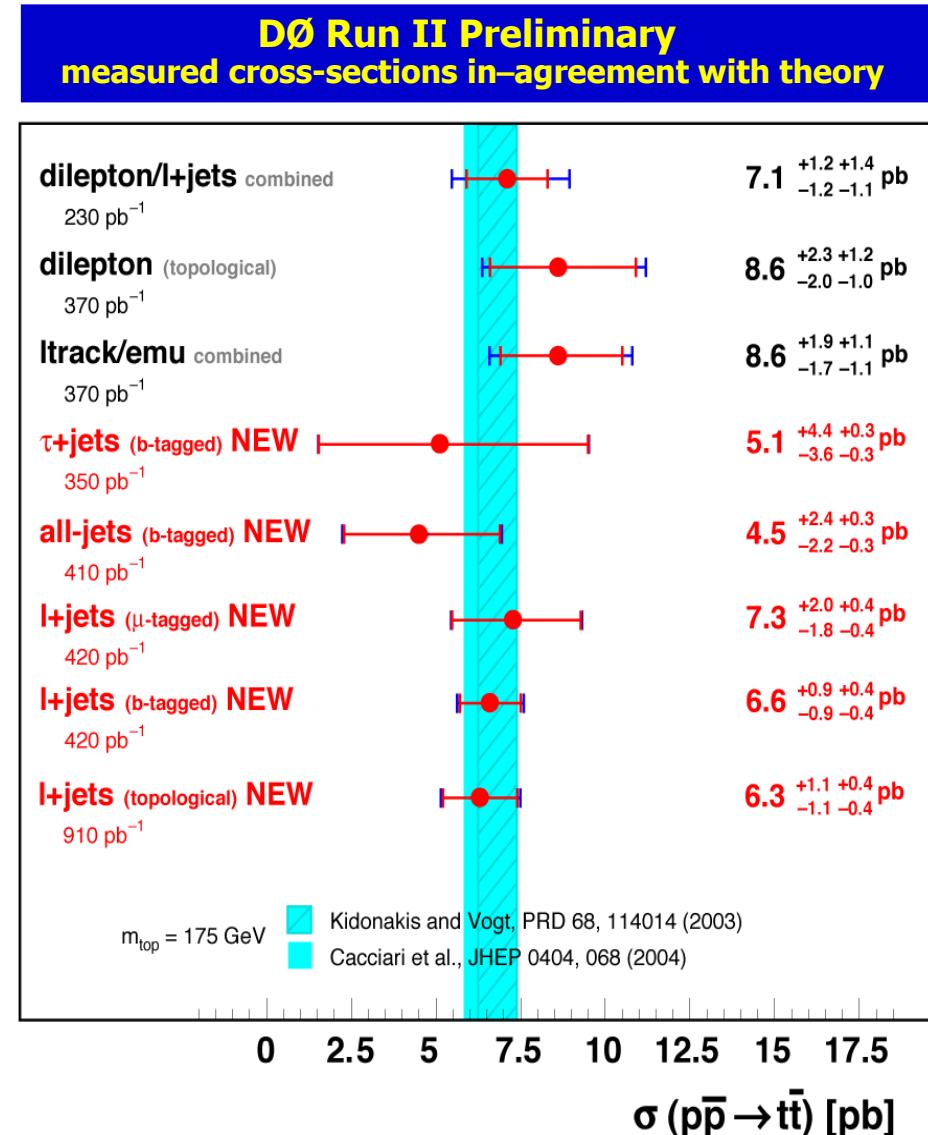
- ...and for  $\tau\text{-type 3}$ :

$$9.39^{+10.10}_{-7.49} (\text{stat})^{+1.25}_{-1.18} (\text{syst}) \pm 0.61 (\text{lum})$$

combined  $\sigma(t\bar{t}) =$

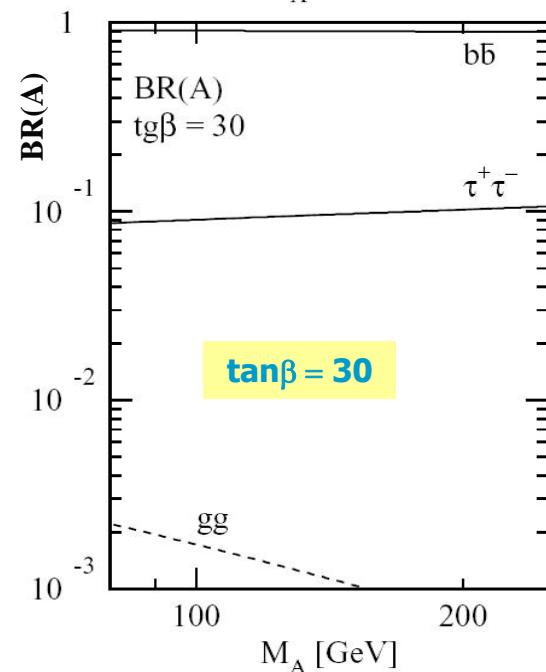
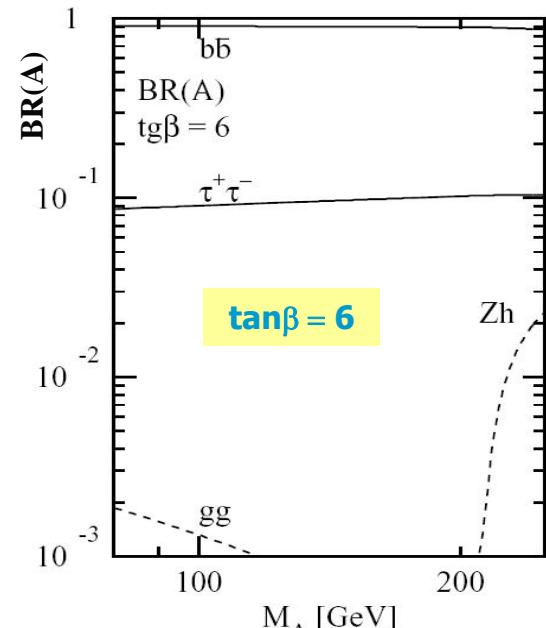
$$5.05^{+4.31}_{-3.46} (\text{stat})^{+0.68}_{-0.67} (\text{syst}) \pm 0.33 (\text{lum})$$

- dominant uncertainty: statistical  $\Rightarrow$  expect significant improvement with  $1 \text{ fb}^{-1}$  data



# MSSM Higgs $\rightarrow\tau\tau$ Searches

- MSSM Higgs requires 2 doublets  $\Rightarrow$  5 physical Higgs bosons
  - two neutral CP-even:  $h^0, H^0$
  - one neutral CP-odd:  $A^0$
  - charged pair:  $H^+$  and  $H^-$
- at tree-level, MSSM higgs fully specified by two free parameters
  - $M_A$  and  $\tan\beta = v_2/v_1$   
( $v_2, v_1$ : vacuum expectation values of two Higgs doublets)
- $\sigma(gg \rightarrow h/H/A) \propto \tan^2 \beta$ 
  - at high  $\tan\beta$ , (low  $M_A$ ), enhanced production cross-section provides golden search mode
- $h/H/A$  decays, in most parameter space:
  - $h/H/A \rightarrow b\bar{b}$  (~90%)
  - $h/H/A \rightarrow \tau\tau$  (~10%)
    - \* smaller BR but  $\tau$  mode  $\Rightarrow$  cleaner signature (vs. large QCD background in  $b$  mode)



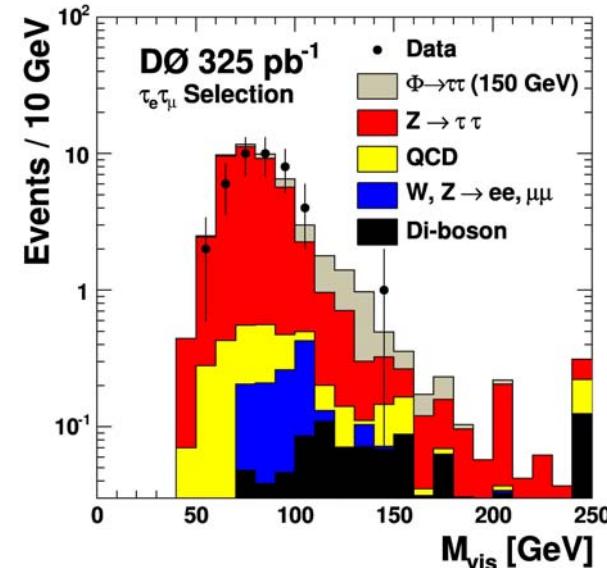
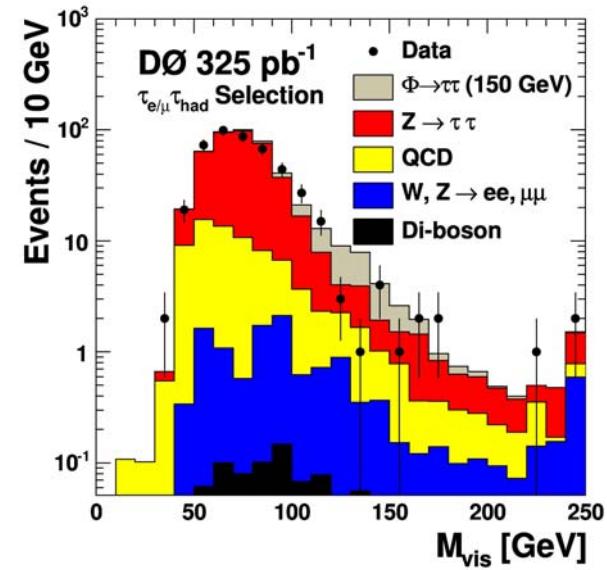


# Inclusive Neutral Higgs $\Phi \rightarrow \tau\tau$

- PRL (325 pb<sup>-1</sup>)  $h/H/A \rightarrow \tau\tau$  search considers final states:  $e\tau_{had}$ ,  $\mu\tau_{had}$ , and  $e\mu$ 
  - $ee, \mu\mu$  not considered  $\Rightarrow$  large  $Z/\gamma^* \rightarrow \mu\mu$  or  $Z/\gamma^* \rightarrow ee$  background  $\Rightarrow$  small S/B
- **signal:** two leptons, missing transverse momentum, and little jet activity
- **Event Selections**
  - in  $e\tau_{had}, \mu\tau_{had}$ 
    - \*  $p_T^{e/\mu} > 14$  GeV and  $E_T^\tau > 20$  GeV, isolated leptons,  $E_T' > 14$  GeV
  - in  $e\mu$ 
    - \*  $p_T^{e/\mu} > 14$  GeV, isolated leptons,  $E_T' > 14$  GeV
  - suppress  $W +$  jet background by anti- $W$  cut:  $M_T^W < 20$  (10) GeV for  $e\tau, \mu\tau$  ( $e\mu$ )
  - suppress  $t\bar{t}$  background by  $H_T < 70$  GeV
  - $NN_{had} > 0.9$  (0.95) for  $\tau$ -types 1, 2 (3)
- Use  $M_{vis}$ , the invariant mass of the sum of the  $\tau$  plus missing transverse energies, to set the limit

$$M_{vis} = \sqrt{(P^\mu + P^\tau + P'_T)}$$

- $P^\mu, P^\tau$  are 4-vectors of  $\mu, \tau$ ; and  $P'_T = (E'_T, E_x, E_y, 0)$

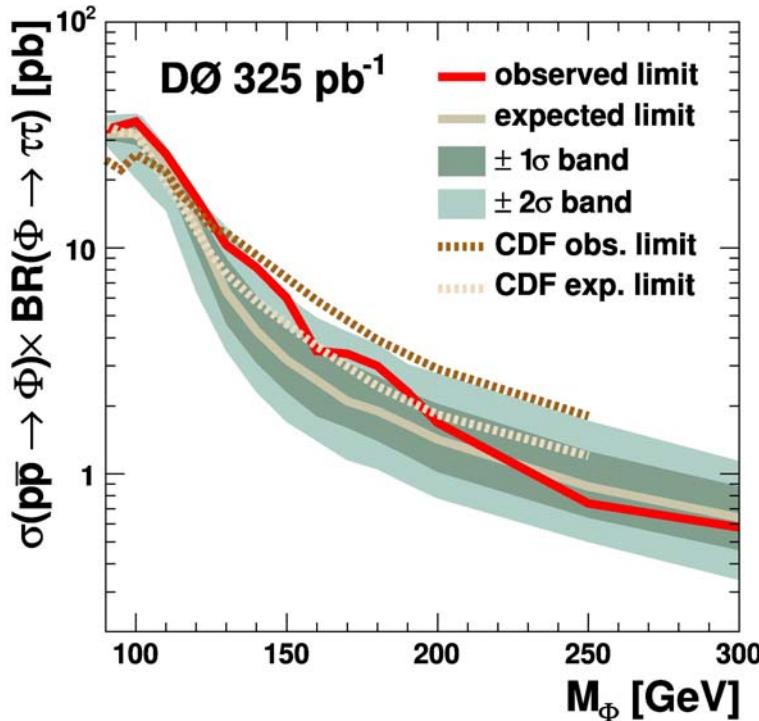


# PRL Result

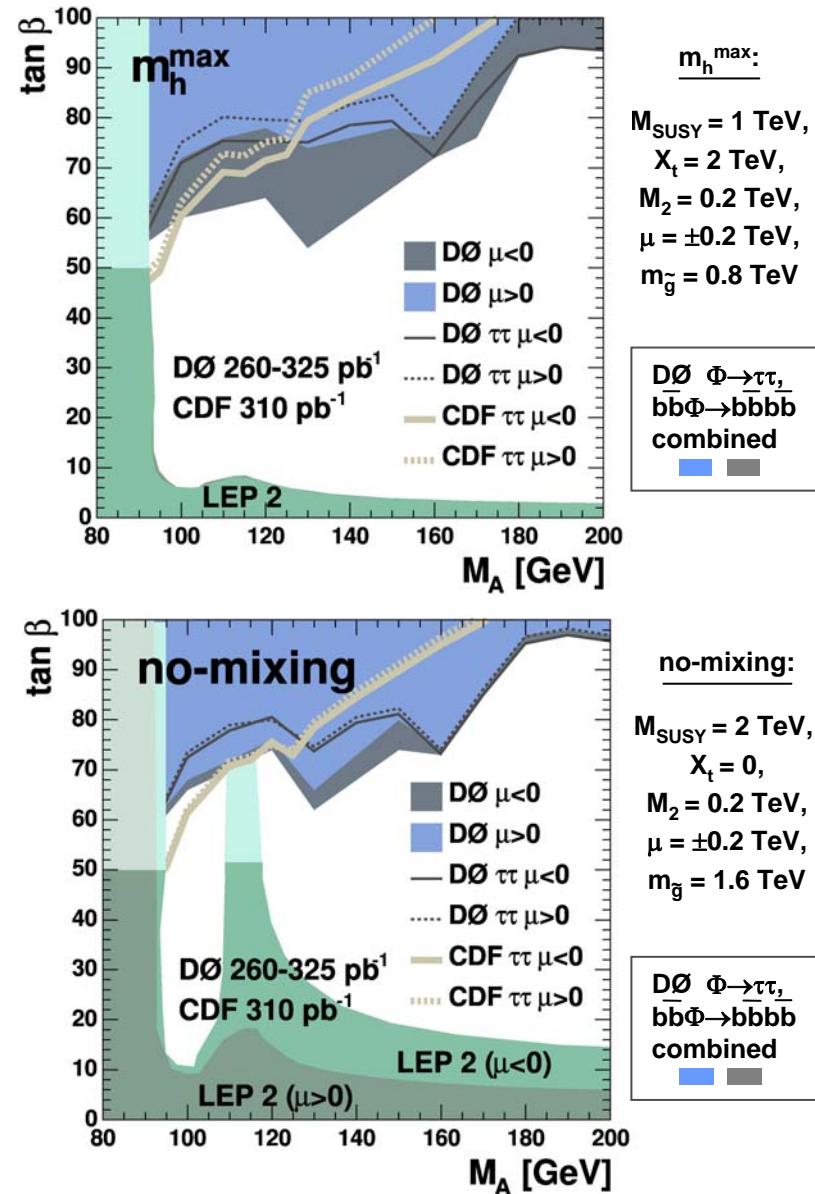
Event Yields and efficiency ( $\varepsilon$ ):  $M_\Phi = 150 \text{ GeV}$

	Data	Total Background	$\varepsilon$ (%)
$e + \tau$	<b>484</b>	<b><math>427 \pm 55</math></b>	<b><math>4.8 \pm 0.4</math></b>
$\mu + \tau$	<b>575</b>	<b><math>576 \pm 62</math></b>	<b><math>8.6 \pm 0.8</math></b>
$e + \mu$	<b>41</b>	<b><math>44 \pm 5</math></b>	<b><math>4.3 \pm 0.5</math></b>

- No significant evidence for Higgs production  $\Rightarrow$  upper limits on  $\sigma \times \text{BR}$



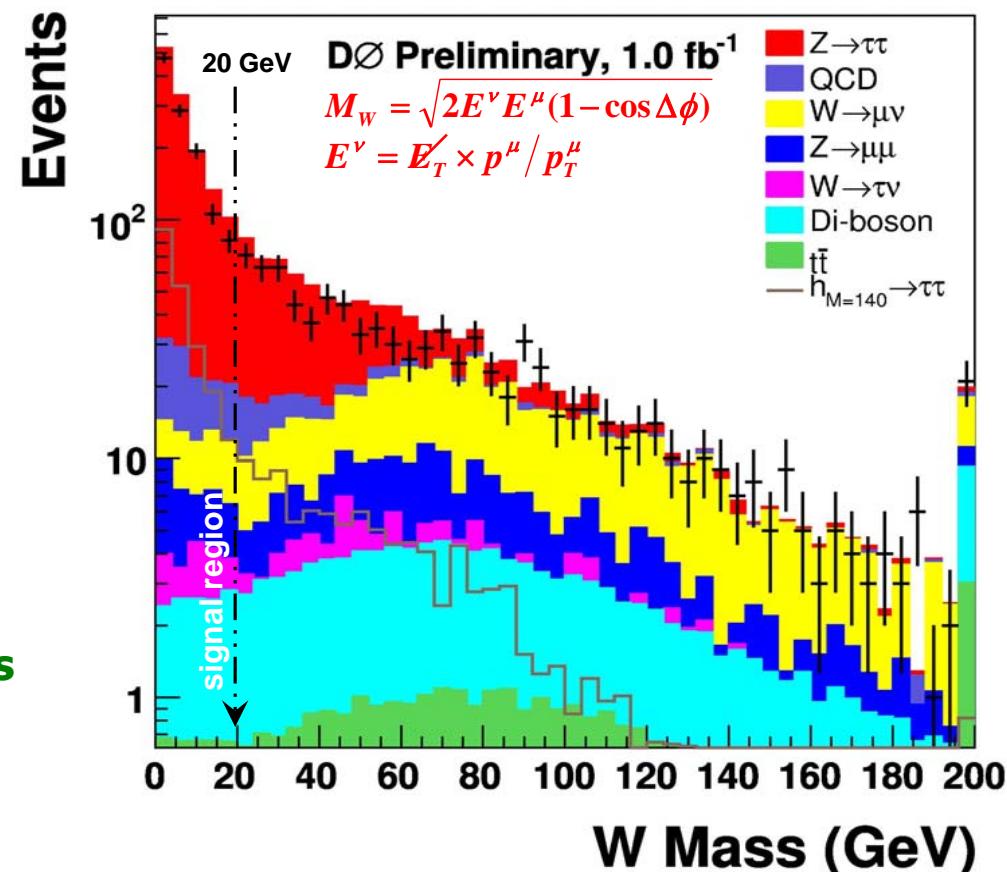
- Interpreted in MSSM  $\Rightarrow 95\% \text{ CL}$  exclusion limits in  $(M_A, \tan\beta)$  plane





# Neutral Higgs $\Phi \rightarrow \tau\tau$ ...Update Result

- Updated  $1 \text{ fb}^{-1}$  (Run IIb) result considers  $h/H/A \rightarrow \tau\tau$  with  $\mu\tau_{\text{had}}$  decay
  - $e\tau_{\text{had}}$  final state presently under study with full Run 2b dataset
- major improvement  $\Rightarrow$  use kinematic NN to improve signal–background separation
- initial event selections similar in strategy as PRL measurement
  - $p_T^\mu > 15 \text{ GeV}$ , isolated muon
  - $E_T^\tau > 15 (20) \text{ GeV}$  for  $\tau$ -type 1, 2 (3) and  $E_T^{\neq} > 20 \text{ GeV}$
  - $\tau\text{-NN} > 0.9 (0.95)$  for  $\tau$ -types 1, 2 (3)
- W-veto: reject  $M_W > 20 \text{ GeV}$ 
  - signal and  $Z \rightarrow \tau\tau$  peak at low W mass
- kinematic NN helps separates signal from backgrounds
  - trained via Higgs MC (signal) and weighted sum of the backgrounds
  - exploit fact that signal resonates at masses higher than  $Z \rightarrow \tau\tau$
  - variables:  $M_{\text{vis}}$ ,  $p_T^\mu$ ,  $E_T^\tau$ ,  $p_T^{\tau-\text{trk}}$ ,  $\eta_\mu$ ,  $\eta_\tau$

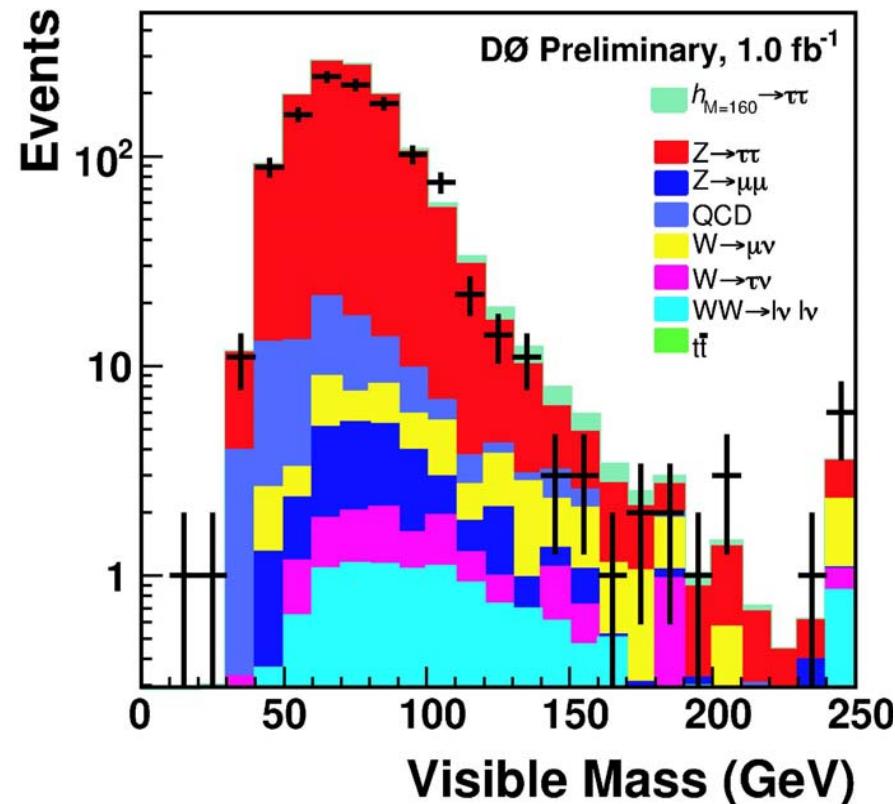
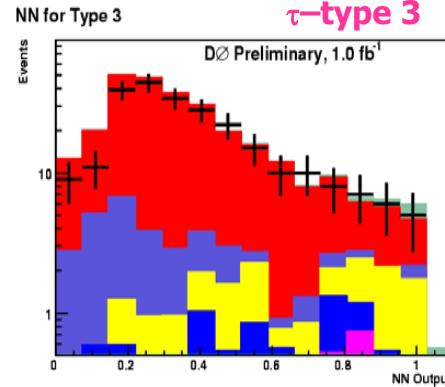
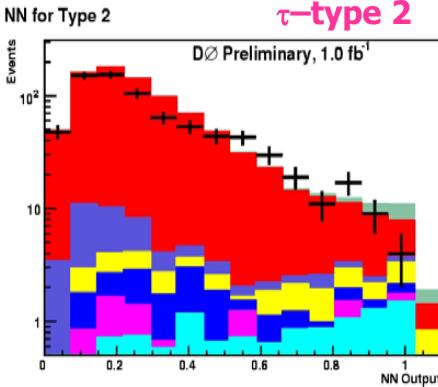
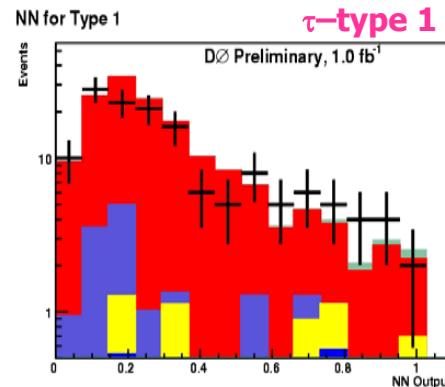
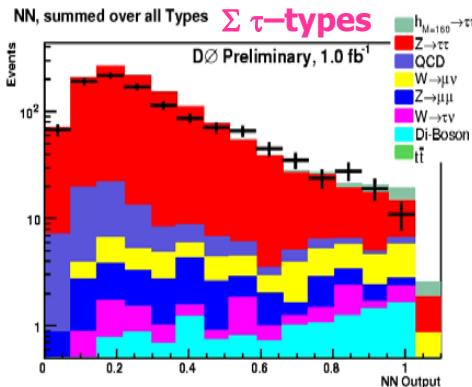




# Higgs $\Phi \rightarrow \tau_\mu \tau_{\text{had}}$ ...1 $\text{fb}^{-1}$ Update Result (cont.)

Kinematic NN: all  $\tau$ -types, 1, 2, and 3 ( $M_\Phi = 160 \text{ GeV}$ )

$M_{\text{vis}}$  Distribution ( $M_\Phi = 160 \text{ GeV}$ )



- data consistent with backgrounds
- maximize sensitivity (~10–40% improvement)  $\Rightarrow$  kNN used in limit calculation

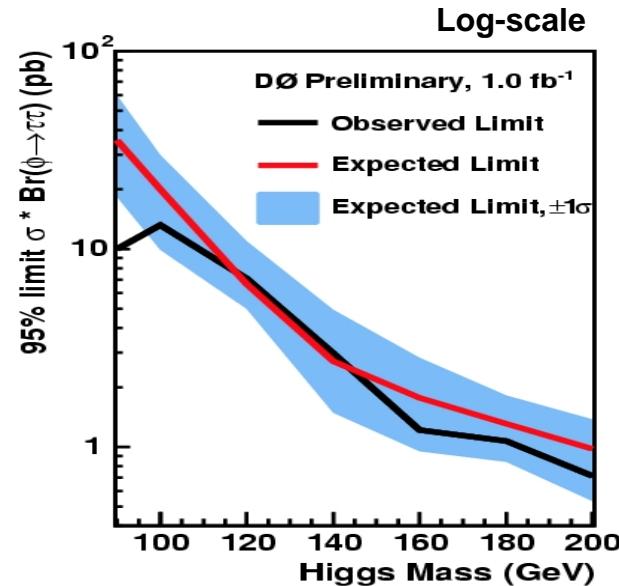
$$M_{\text{VIS}} = \sqrt{(P^\mu + P^\tau + P'_T)}$$

- $P^\mu, P^\tau$  are four-vectors of  $\mu$  and  $\tau$
- $P'_T = (E'_T, E_x, E_y, 0)$

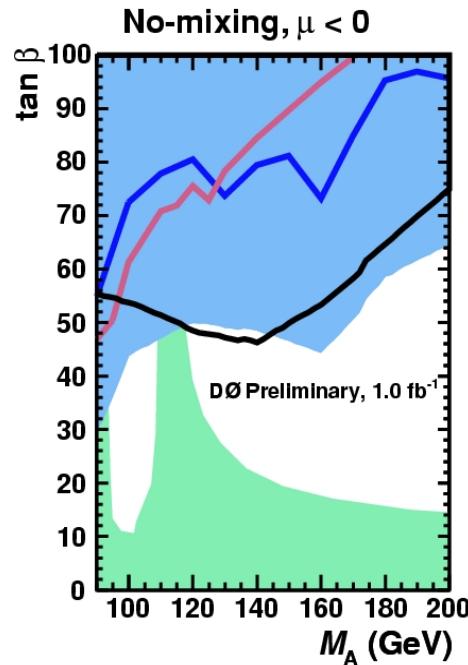
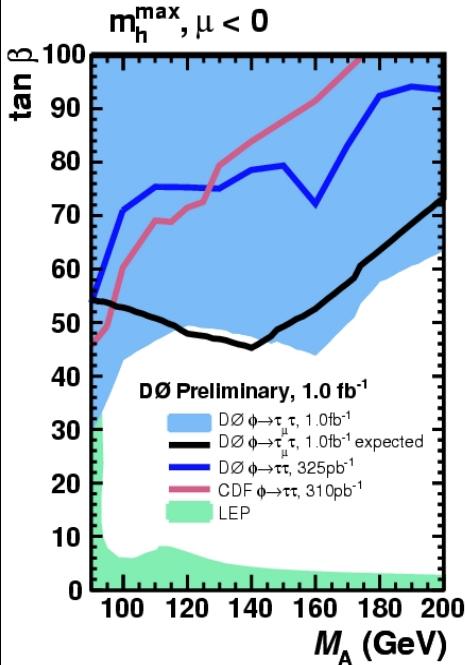


# 1 $\text{fb}^{-1}$ result (cont.)

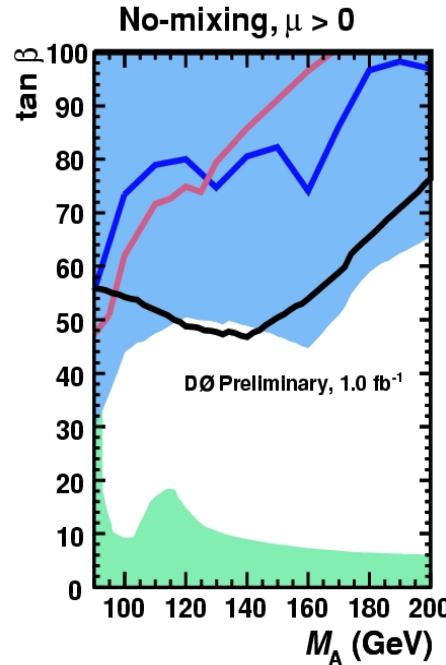
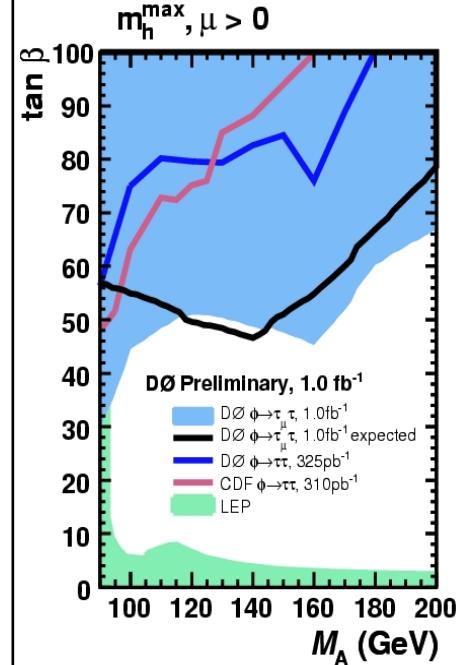
- derive limits on  $\sigma \times \text{BR}$  at 95% CL
- DØ's rebuttal to CDF's result shown at Aspen Winter 2007 conference
  - CDF excess seen at  $M_A \sim 160 \text{ GeV}$ ,  $\tan\beta \sim 50$
  - DØ:  $90 \leq M_A \leq 200 \text{ GeV}$  excludes  $\tan\beta \geq 40 \rightarrow 65$



for  $\mu < 0$



for  $\mu > 0$

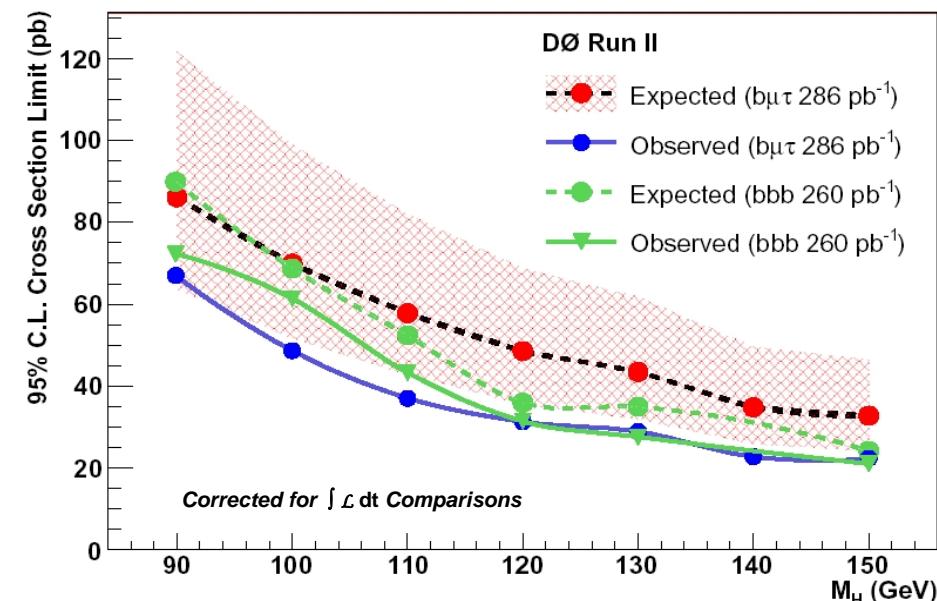


**DØ: Most constraining limits from  $H \rightarrow \tau\tau$  decay channel to date**

# b(h/H/A) → bττ Search

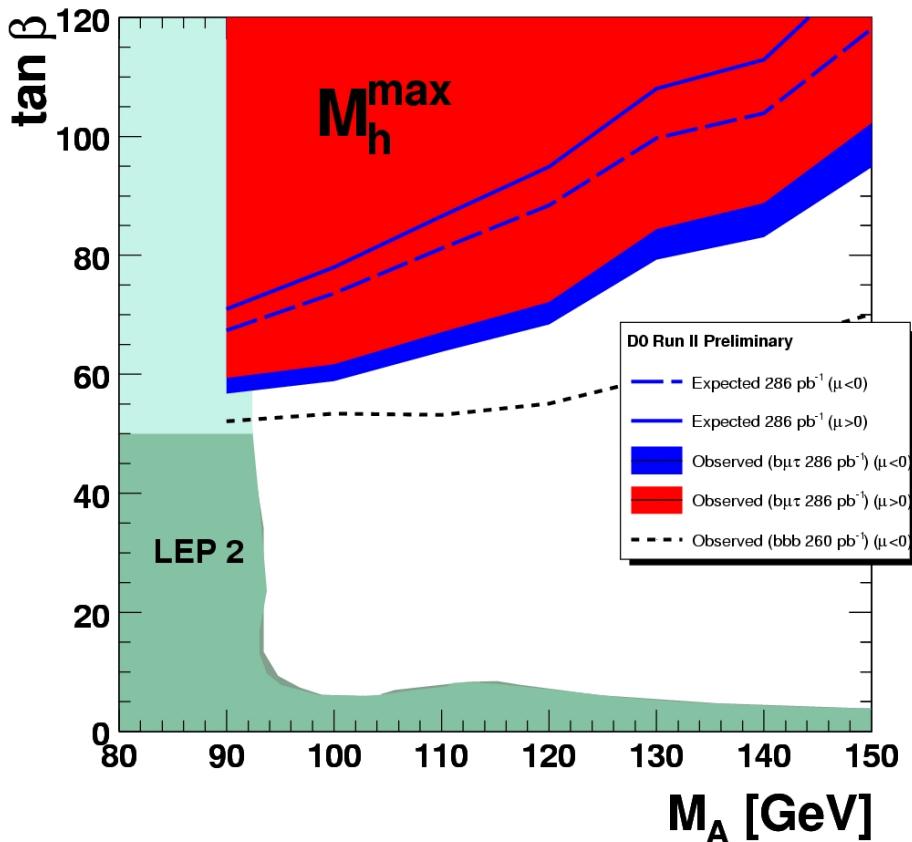
- Neutral Higgs production in association with b quark
  - consider  $bg \rightarrow b(h/H/A) \rightarrow b\tau\tau \rightarrow b\mu\tau_{had}$  final states with  $\int \mathcal{L} dt \rightarrow 344 \text{ pb}^{-1}$
  - analysis strategy built on  $Z \rightarrow \tau\tau$  PRD result and  $\Phi \rightarrow \tau\tau$  results
- Selections require b-tag and  $\tau\text{-NN} > 0.8$  ( $0.98$ ) for  $\tau\text{-types 1, 2 (3)}$ 
  - tight  $\tau\text{-type 3}$  due to suppression of larger multijet backgrounds
- after b-tag, main background due to  $t\bar{t} \rightarrow \mu\tau_{had} + b\bar{b}$ 
  - use kinematic NN to separate signal with top background
  - trained via Higgs MC (signal) and  $t\bar{t} \rightarrow \mu\tau_{had}$  (background)
  - input variables:  $\Sigma E_T$  of all jets per event,  $H_T$ ,  $N_{\text{jets}}$ ,  $\Delta\phi(\mu, \tau_{had})$
- data consistent with background  $\Rightarrow$  95% CL as function of Higgs mass
  - $h \rightarrow \tau\tau$  mode competitive with  $h \rightarrow b\bar{b}$  at low  $M_H$  despite 1:9 branching ratio

For $M_H = 120 \text{ GeV}$	τ-type 1	τ-type 2	τ-type 3
Acceptance (%)	$0.15 \pm 0.03$	$0.87 \pm 0.11$	$0.27 \pm 0.04$
Expected Signal ( $\tan\beta=80$ )	$0.7 \pm 0.1$	$3.9 \pm 0.6$	$1.2 \pm 0.2$
Total Background	$1.2 \pm 0.2$	$2.6 \pm 0.3$	$1.7 \pm 0.2$
Observed	0	1	2

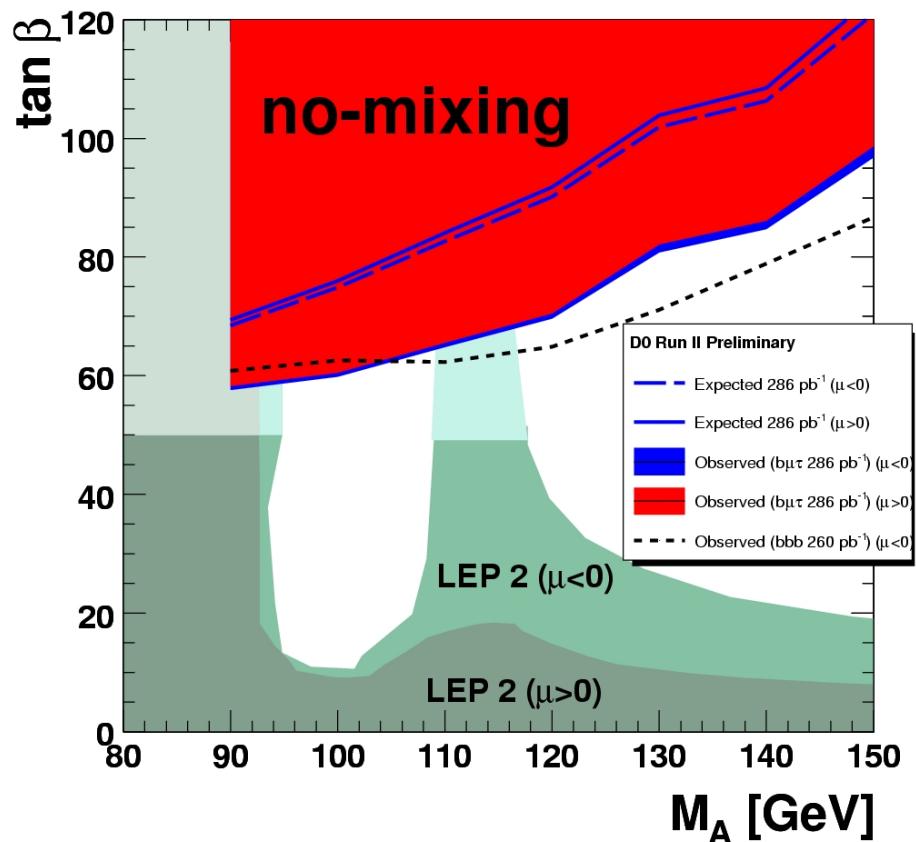


# b(h/H/A) → bττ Interpretation in MSSM

$M_h^{\max}$ :  $M_{\text{SUSY}} = 1 \text{ TeV}$ ,  $X_t = 2 \text{ TeV}$ ,  $M_2 = 0.2 \text{ TeV}$ ,  
 $\mu = \pm 0.2 \text{ TeV}$ ,  $m_{\tilde{g}} = 0.8 \text{ TeV}$



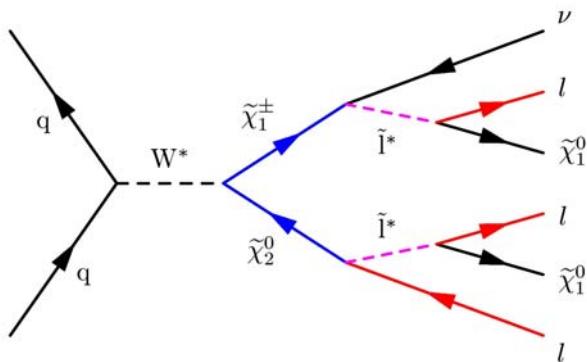
no-mixing:  $M_{\text{SUSY}} = 2 \text{ TeV}$ ,  $X_t = 0$ ,  $M_2 = 0.2 \text{ TeV}$ ,  
 $\mu = \pm 0.2 \text{ TeV}$ ,  $m_{\tilde{g}} = 1.6 \text{ TeV}$



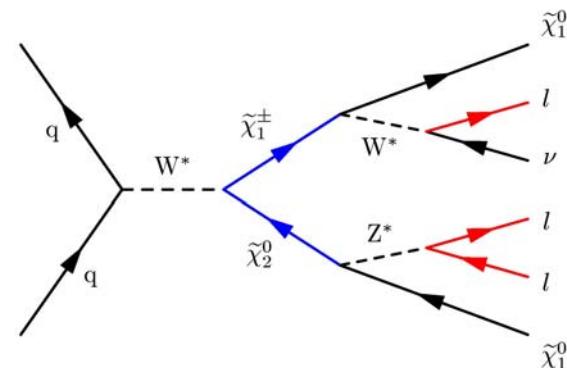
- limits derived on  $\tan \beta$  for different  $M_A$  in  $M_h^{\max}$  scenario and no-mixing scenarios
  - negative values of Higgsino mass parameter,  $\mu$ :  $\tau\tau$  mode comparable to  $b\bar{b}$
  - positive values of  $\mu$ :  $\tau\tau$  mode appears better than  $b\bar{b}$ , especially at lower masses

# SUSY: trilepton decays in mSUGRA (RPC)

Pair Production and Decay via sleptons



Pair Production and Decay via gauge bosons



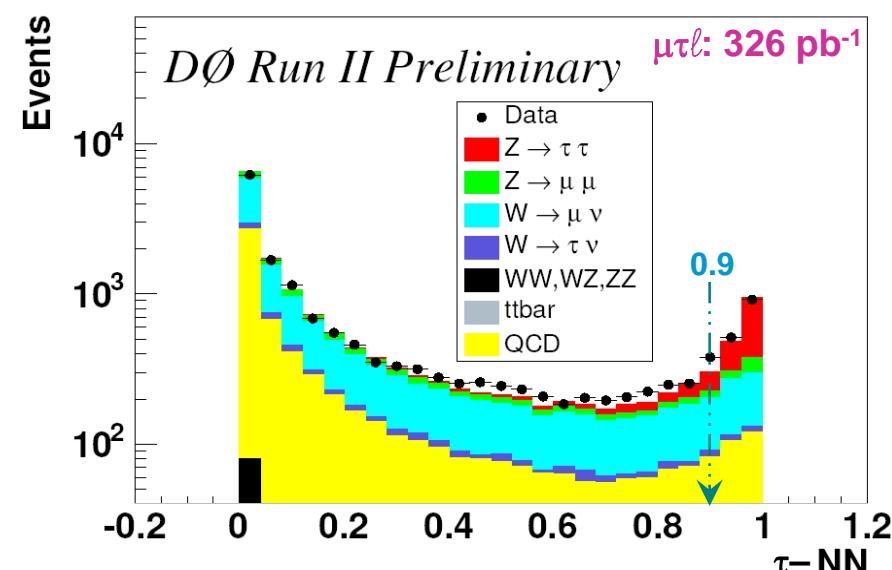
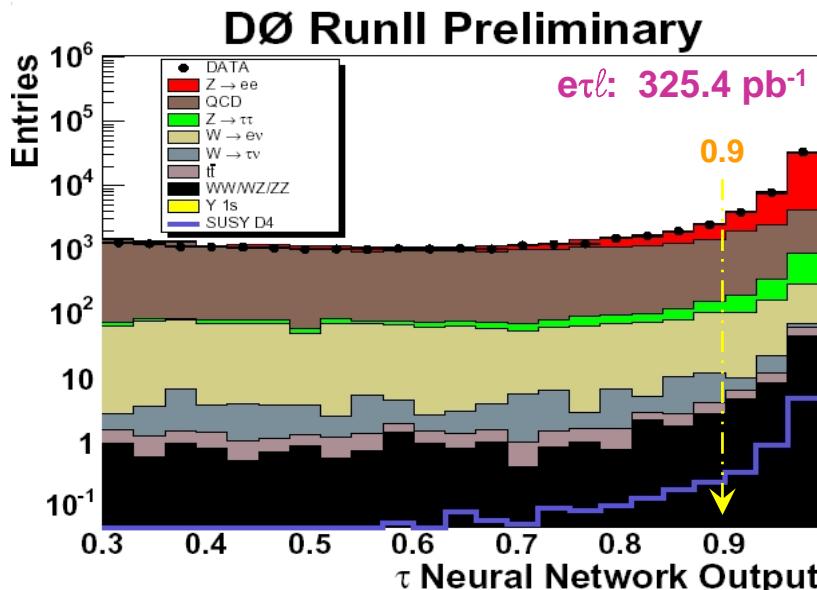
- Search for associated production of charginos and neutralinos in trilepton channel
  - cascade decay with striking signature: 3 low  $p_T$  leptons +  $E_T$
  - promising channel  $\Rightarrow$  small backgrounds from SM
- Consider six topologies (where  $\ell$  = isolated track, may be e,  $\mu$ , or  $\tau$ )

Topology	DØ $\int \mathcal{L} dt$ analysis
eel	1.1 $fb^{-1}$ [updated]
e $\mu\ell$	325 $pb^{-1}$ [PRL 95 151805 (2005)]
$\mu\mu\ell$	325 $pb^{-1}$ [PRL 95 151805 (2005)]
like-sign $\mu\mu$	0.9 $fb^{-1}$ [updated]
e $\tau\ell$	325 $pb^{-1}$
$\mu\tau\ell$	325 $pb^{-1}$

- e $\tau\ell$  and  $\mu\tau\ell$  reported here  $\Rightarrow$  increased sensitivity on cross section limits when combined with first 4 topologies

# e $\tau\ell$ and $\mu\tau\ell$ : Signal Selection

- Search uses single e or single  $\mu$  triggers
- $e\tau\ell$  selections
  - isolated electron:  $p_T^e > 8 \text{ GeV}$ ,  $|\eta| < 1.0$
  - $E_T > 25 \text{ GeV} \Rightarrow$  helps suppress  $Z/\gamma \rightarrow ee$  and QCD multi-jet backgrounds
  - consider 1-prong  $\tau$ 's (types 1, 2) with  $p_T^\tau > 8 \text{ GeV}$  and  $NN > 0.9$
- $\mu\tau\ell$  selections
  - isolated muon:  $p_T^\mu > 14 \text{ GeV}$ ,  $|\eta| < 2.0$
  - $E_T > 20 \text{ GeV} \Rightarrow$  helps suppress  $Z/\gamma \rightarrow \mu\mu$  and QCD multi-jet backgrounds
  - consider 1-prong  $\tau$ 's (types 1, 2) with  $p_T^\tau > 7 \text{ GeV}$  and  $NN > 0.9$

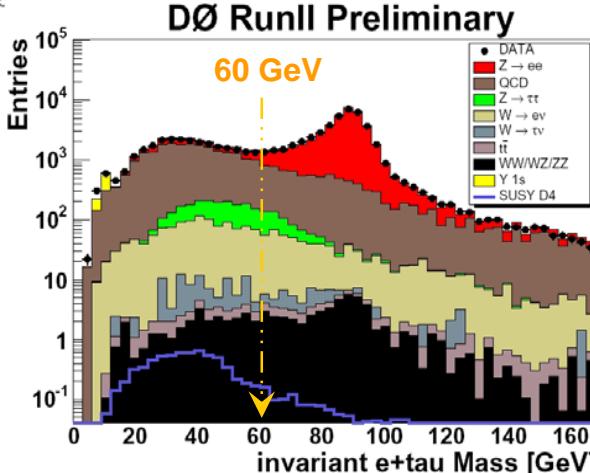




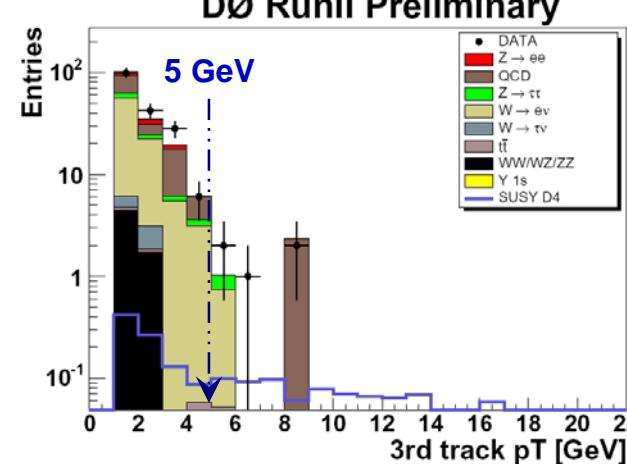
# $e\tau l$ and $\mu\tau l$ : Signal – Background separation

- $NN > 0.9$  helps reduce QCD multijet background from 1-prong  $\tau$ 's
- Further selections help reduce major backgrounds
  - **Z-veto:** keep events with  $m(\ell, \tau) < 60$  GeV; veto back-to-back:  $\Delta\phi(\ell, \tau) > 2.9$
  - **W-veto:** exploit fact that 3<sup>rd</sup> charged lepton exists in SUSY final state
    - \* require additional isolated lepton,  $p_T^{3\text{rd-trk}} > 5$  GeV
    - \* remove events in  $50 < m_T(\ell, E_T) < 90$  GeV
  - **Diboson-veto:** exploit 3<sup>rd</sup> track
    - \* W-veto
    - \* remove events  $\Rightarrow m(\ell_{1,2}, \ell_3)$  consistent with Z mass and  $\Delta\phi(\ell_3, E_T) < 0.4$
  - **t̄t-veto:**  $H_T < 60$  GeV
  - **mis-measured reco'd objects gives large  $E_T$  in QCD events  $\Rightarrow E_T$  significance:**
    - \* scaled  $E_T = E_T / \sqrt{\sum_{\text{jets}} (\sqrt{E_{\text{jet}}} \times \sin \theta_{\text{jet}} \times |\cos \Delta\phi(\text{jet}, E_T)|)^2} > 8 \sqrt{\text{GeV}}$

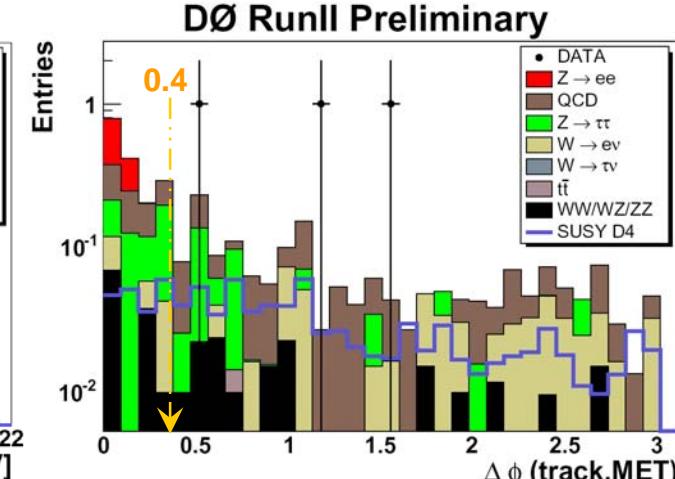
a) Z-Veto:



b) W- (and Diboson-) Veto:



c) Diboson-Veto:



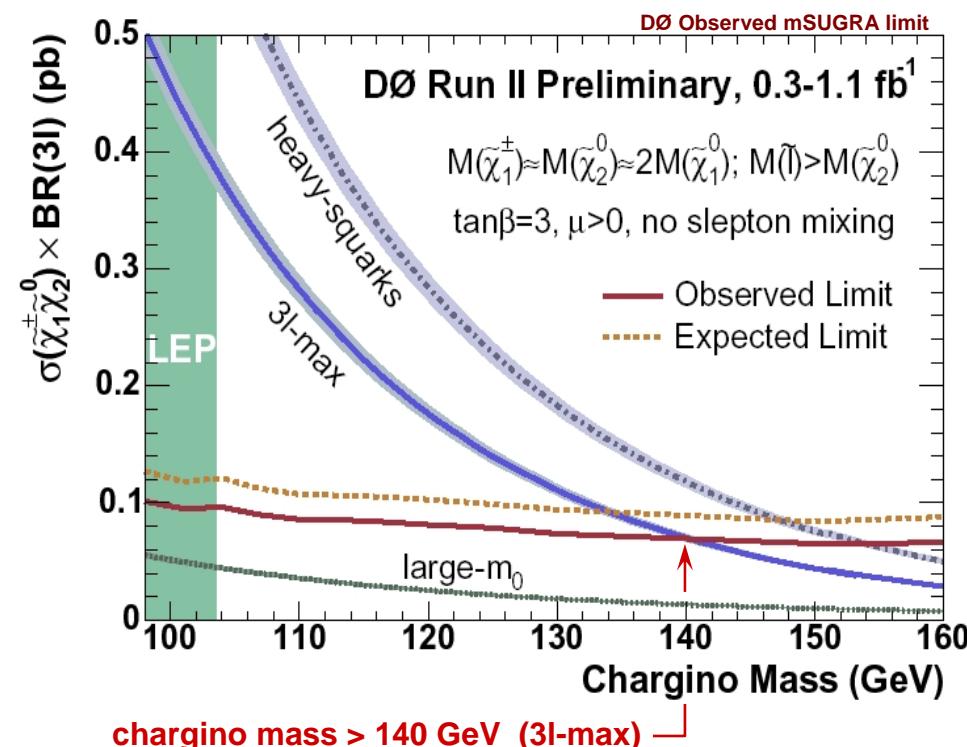
# SUSY limits: $\sigma \times \text{BR}$ trilepton final states

Topology	Data	Expected Background	Signal
eel	0	$0.76 \pm 0.67$	$1.7 \pm 0.1$
e $\mu\ell$	0	$0.31 \pm 0.13$	$1.6 \pm 0.1$
$\mu\mu\ell$	2	$1.75 \pm 0.57$	$1.3 \pm 0.2$
like-sign $\mu\mu$	1	$1.10 \pm 0.40$	$1.3 \pm 0.1$
e $\tau\ell$	0	$0.58 \pm 0.11$	$0.6 \pm 0.1$
$\mu\tau\ell$	1	$0.72 \pm 0.26$	$0.8 \pm 0.1$

Selections based on Signal:

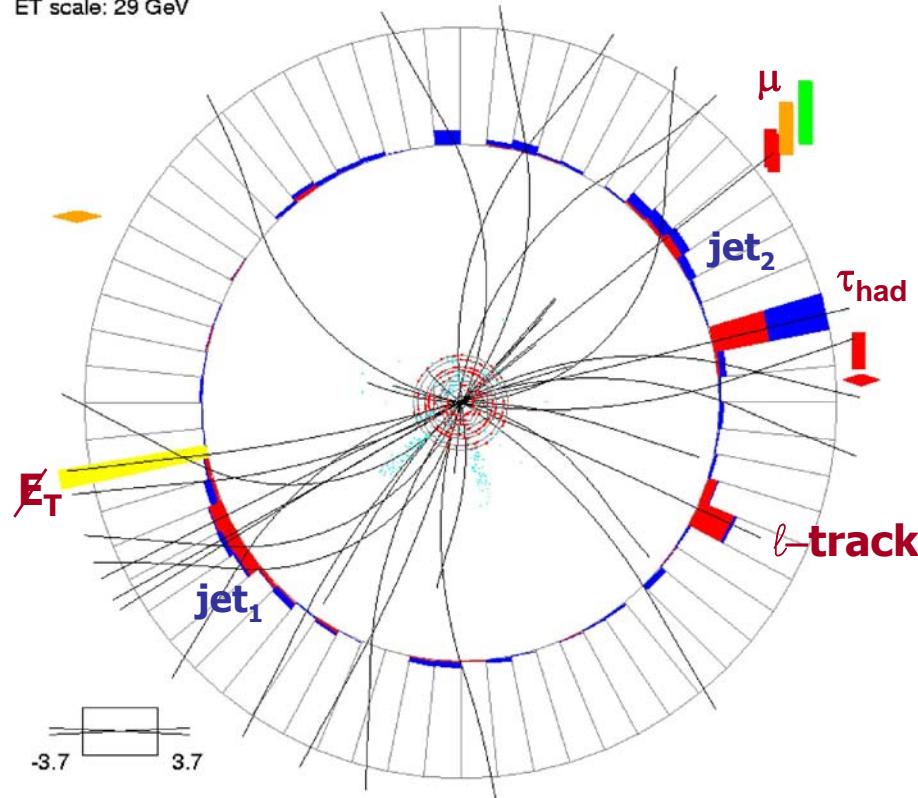
$$\begin{aligned} \tan\beta &= 3, \mu > 0 \\ m_{\tilde{\chi}^\pm} &= 110 \text{ GeV}, \quad m_{\tilde{\chi}^0} = 62 \text{ GeV} \end{aligned}$$

- Data consistent with backgrounds  $\Rightarrow$  upper limits on  $\sigma(\tilde{\chi}_1^\pm \tilde{\chi}_2^0) \times \text{BR}(3\ell)$
- Compared in general SUSY scenarios
  - heavy-squarks (light sleptons, heavy squarks)  $\Rightarrow$  maximal leptonic  $\sigma \times \text{BR}$
  - 3l-max ( $m_{\tilde{t}} \sim m_{\tilde{\chi}}$ )  $\Rightarrow$  decay rates into leptons are large
  - large- $m_0$  (heavy sleptons & squarks)  $\Rightarrow$  W/Z exchange dominant in  $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$  decays
- for Ref., 325 pb $^{-1}$  PRL set chargino mass  $> 117$  GeV (132 GeV) for 3l-max (heavy squarks)

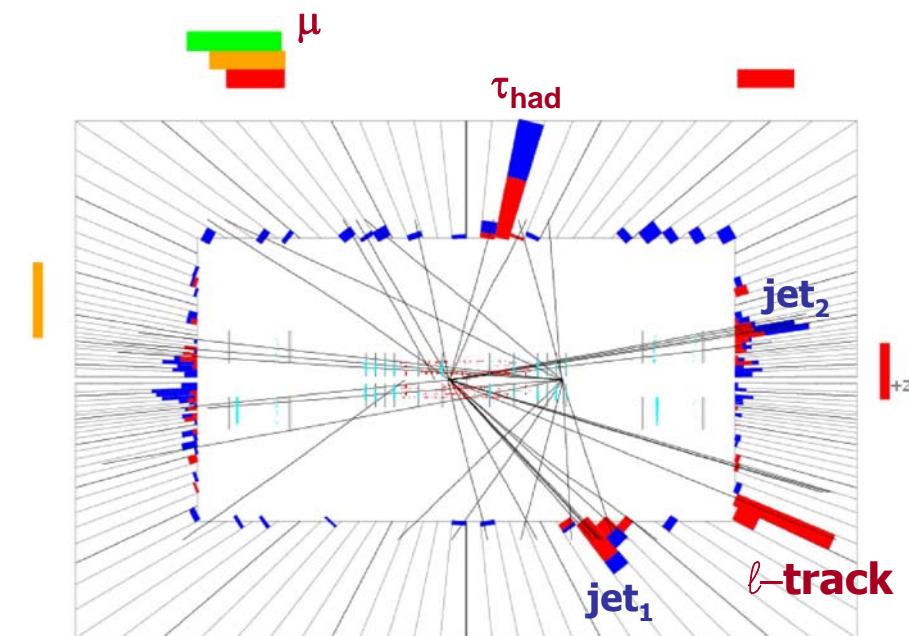


$\mu\tau\ell + E_T$  Event Signature at DOr-z plane ( $\phi$ )

ET scale: 29 GeV

x-y plane ( $\eta$ )

E scale: 25 GeV



- Electromagnetic Energy
- Hadronic Energy
- Missing Transverse Energy

- Central Tracking
- Muon a,b, c-layer hits



# Closing Summary

## Tau Identification

- **DØ exploits Neural Network techniques for  $\tau$  identification**
- **Jet rejections better than 90% can be achieved with  $\tau$  efficiencies near 65%**
- **Misidentified e's and  $\mu$ 's can be reduced to low levels**

## Tau Physics

- **Rich physics program at DØ using  $\tau$  identification; with several analyses underway using large collection of the Run IIa ( $\sim 1.5 \text{fb}^{-1}$ ) data sample**
- **Run IIb (2006 – present) achieving higher luminosities and will allow studying signals beyond SM**
- **Complete Results at:** *[www-d0.fnal.gov/Run2Physics/WWW/results.htm](http://www-d0.fnal.gov/Run2Physics/WWW/results.htm)*
- **Wealth of development and studies of  $\tau$ 's should be valuable for LHC experiments**

# **Reference Slides**

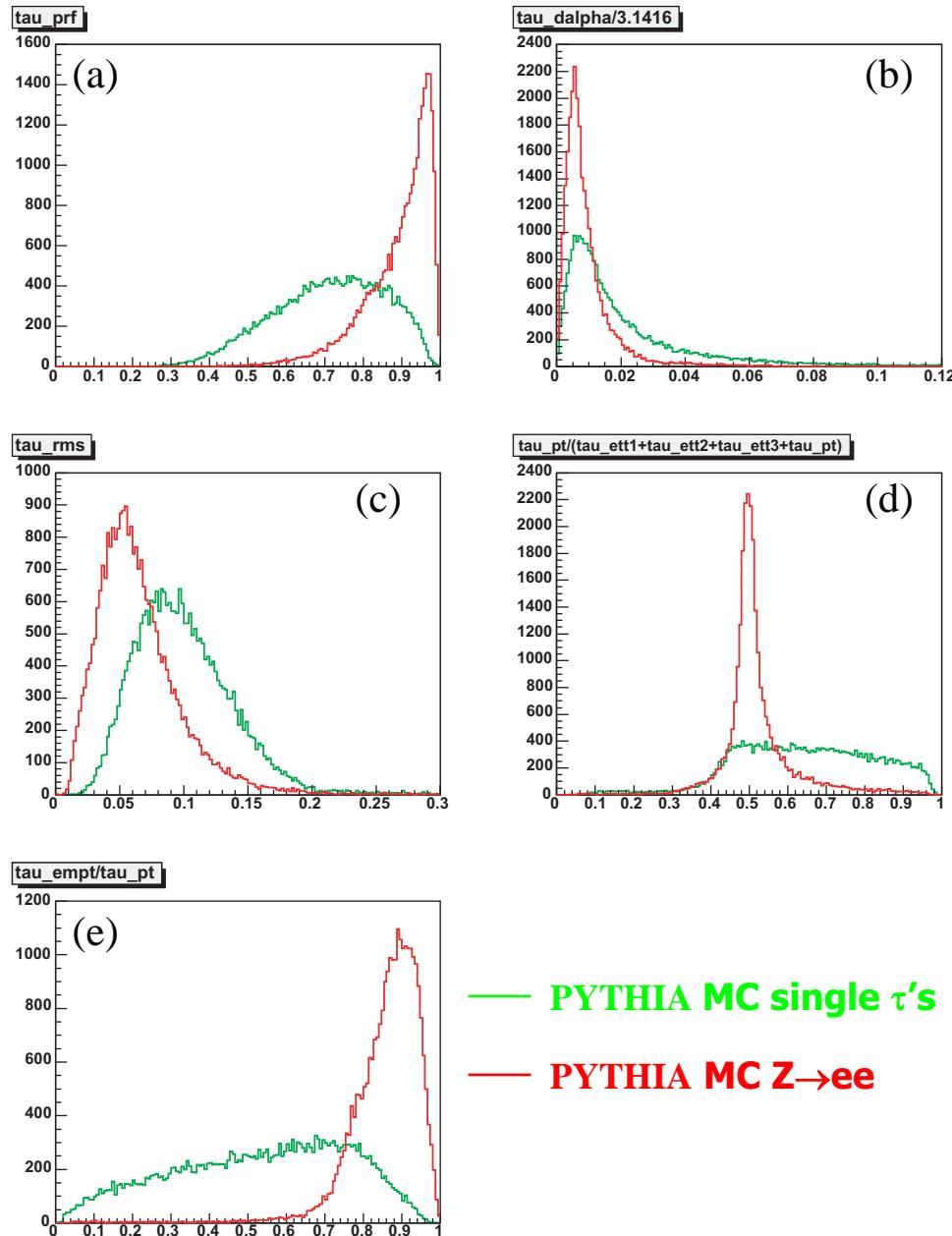


# NN<sub>e</sub> discriminating variables (e- $\tau$ <sub>type 2</sub> separation)

- initial network (NN<sub>had</sub>) developed to separate QCD jets from hadronic  $\tau$ 's
- develop NN to separate electrons from type 2  $\tau$ 's
  - Signal: MC single  $\tau$ 's
  - Background: MC Z $\rightarrow$ ee events

- Five NN<sub>elec</sub> variables

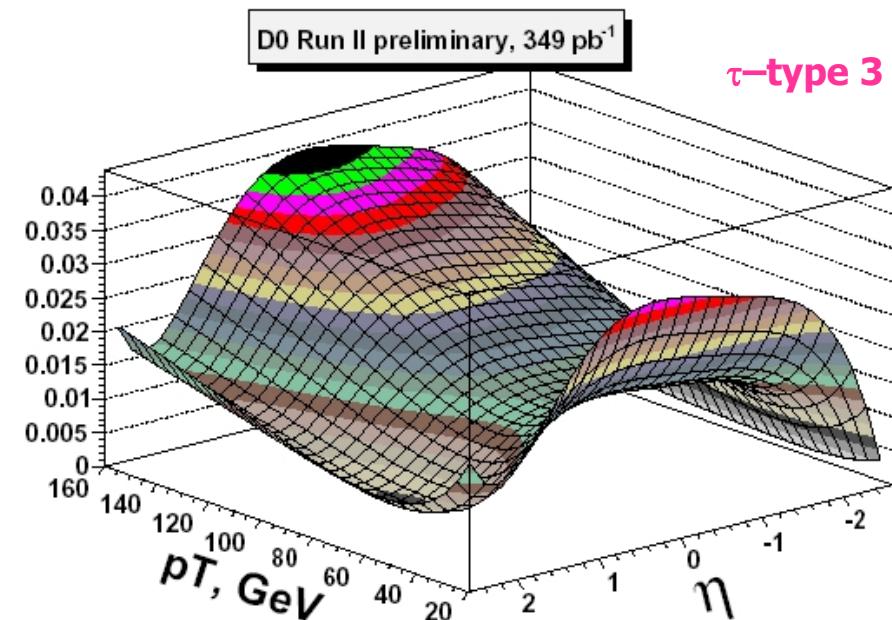
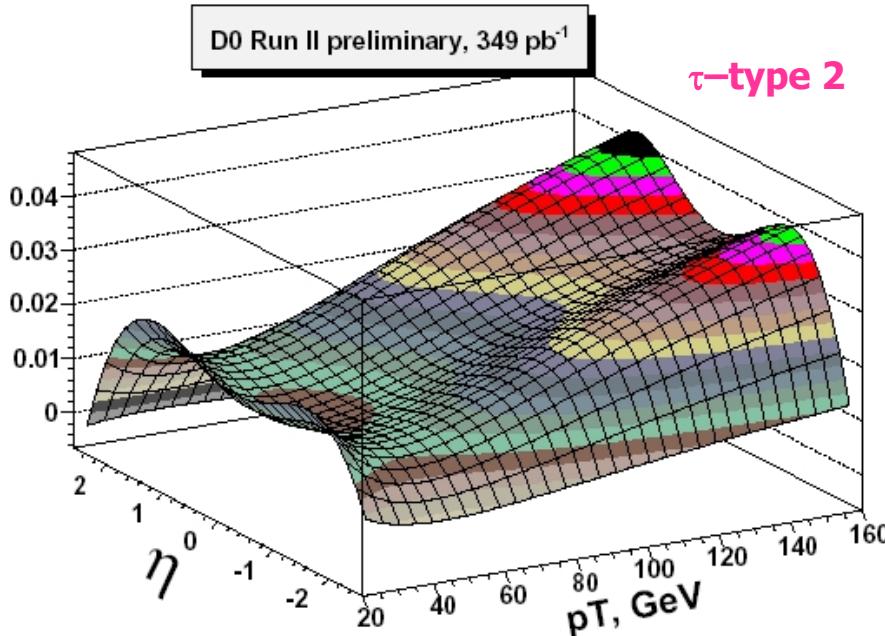
- profile
- $\delta\alpha$
- $rms_{\tau}$  (measures of  $\tau$ -cluster width)
- $E_T^{\tau} / (E_T^{\tau} + \sum p_T^{\tau-trk})$
- $E_T^{EM} / E_T^{\tau}$





# $t\bar{t} \rightarrow \tau + \text{jets}$ cross section: QCD modeling

2D Combined Fit (in  $\eta$  and  $p_T$ ) for QCD  $\tau$  fake rate



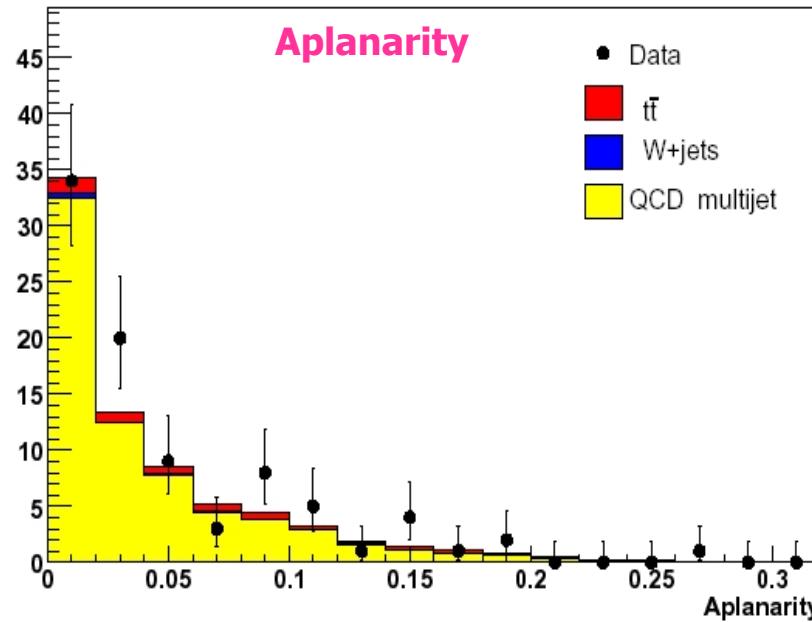
- statistical approach used to model QCD background
  - $\tau$ -signal sample: based on  $\tau$ -NN > 0.95 and require b-tag (268 events)
  - b-veto sample: remove b-tag requirement for QCD estimate (4,642 events)
- b-veto sample: dominated by multi-jet events
- $\tau$ 's are "jets"  $\Rightarrow$  divide  $p_T$  vs.  $\eta$  distribution for  $\tau$  candidates with the same distribution for jets  $\Rightarrow$  parameterize  $\tau$  fake rate by performing 2D fits in ( $p_T$ ,  $\eta$ )
- Probability for jet to fake  $\tau = F(\eta, p_T) = A(\eta)B(p_T)$
- Probability for jet/event (tagged data) will fake  $\tau = P_{event} = 1 - \prod_{j=bin} (1 - F(\eta^j, p_T^j))$

# $t\bar{t} \rightarrow \tau + \text{jets}$ cross section: topological NN

## Topological NN input variables: Aplanarity and $H_T$

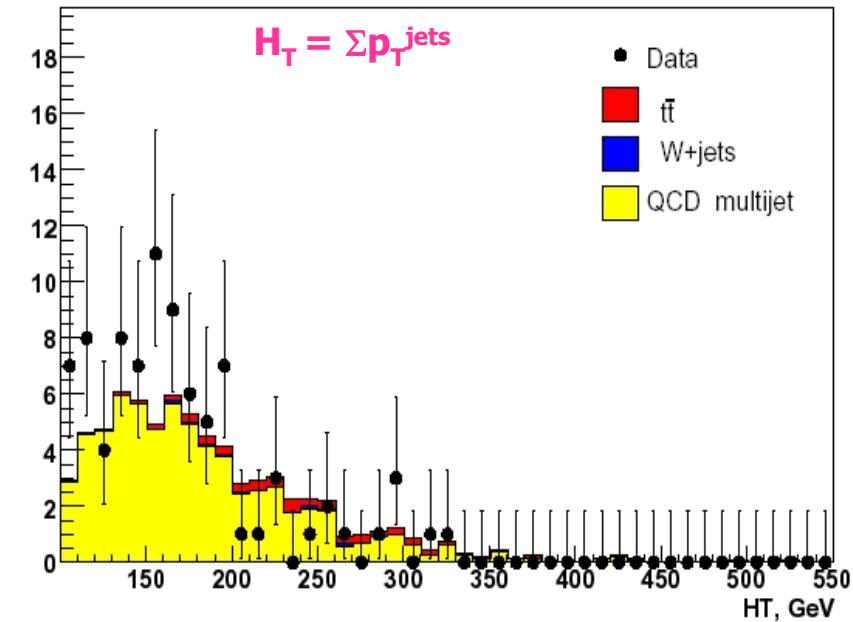
KS Probability: 0.993028

D0 Run II preliminary, 349 pb<sup>-1</sup>



KS Probability: 0.275234

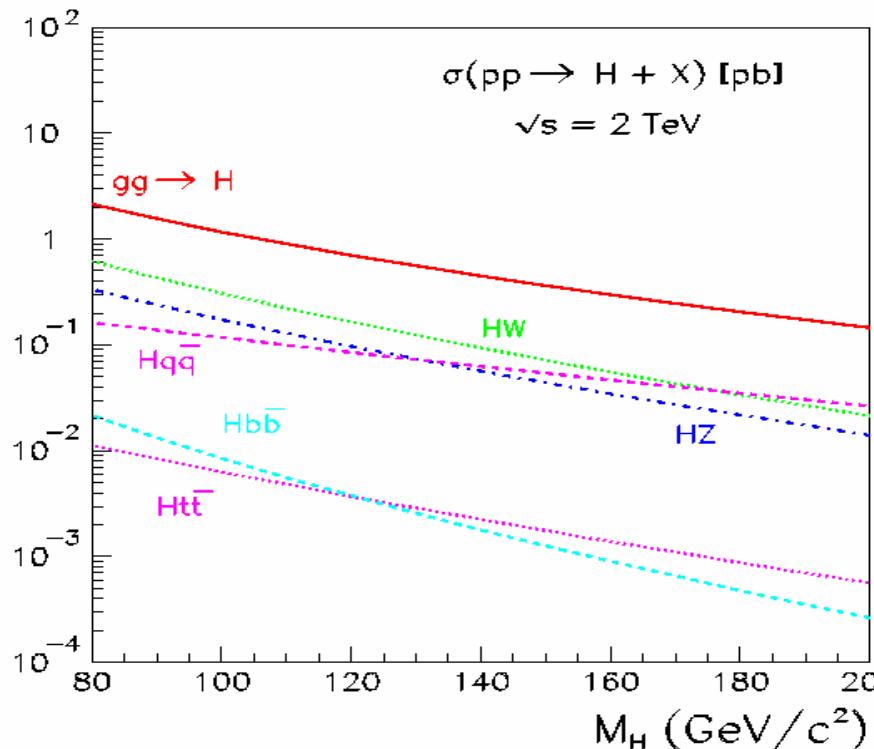
D0 Run II preliminary, 349 pb<sup>-1</sup>



- S:B (post-basic selections and ID requirements, pre-topological NN)  $\sim 1:48$
- S:B (post-topological NN)  $\sim 1.5:1$
- Topological NN based on  $t\bar{t}$  all-jets channel measurement
- Train topological NN via “ $\tau$ -veto” sample for background (from data):  $0 < \tau\text{-NN} < 0.5$ , requiring no good  $\tau$  in event (21,022 events)
- topological NN cut based on maximum signal significance  $\Rightarrow \text{top-NN} > 0.9$

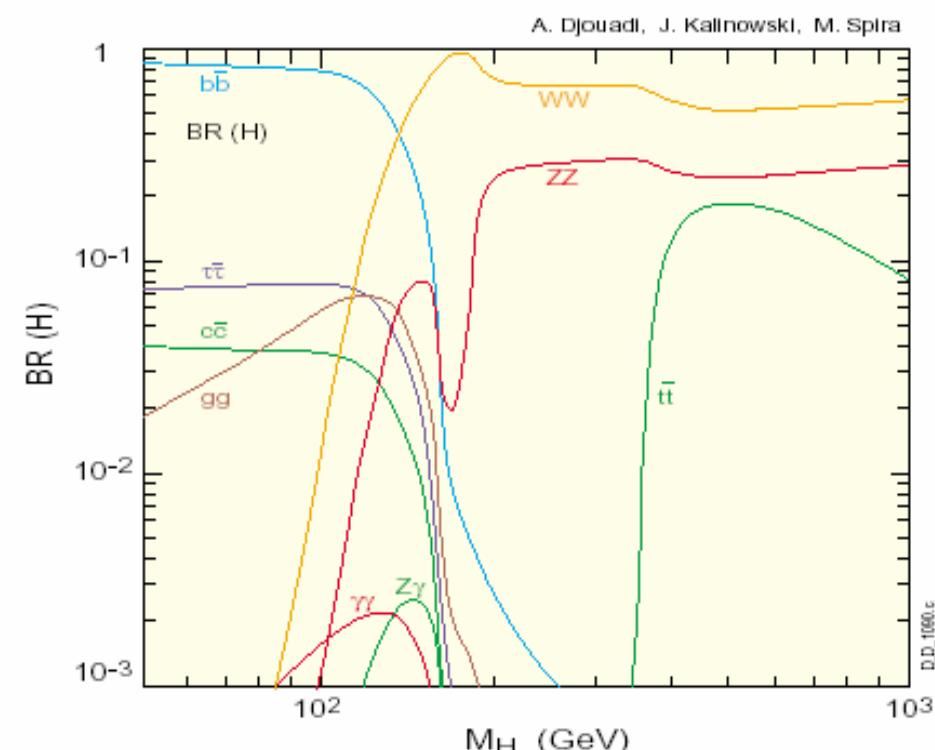
# SM Higgs production x–sec & decays at TeV

## Higgs Production Cross Section



- $gg \rightarrow H$
- $q\bar{q}' \rightarrow W^*/Z^* \rightarrow (W/Z)H$

## Higgs Decay BR



- $M_H \lesssim 135 \text{ GeV: } H \rightarrow b\bar{b}$   
or  $H \rightarrow \tau\tau$
- $M_H \gtrsim 135 \text{ GeV: } H \rightarrow W^+W^-$

MSSM extensions  $\Rightarrow$  Low (High) mass SM Higgs search is  
more relevant (less relevant) for SUSY



# SUSY $e\tau\ell$ channel: Candidate Events

- $\int \mathcal{L} dt = 325.4 \pm 21.2 \text{ pb}^{-1}$
- Cut flow  $\Rightarrow$  candidate events observed (Data) and expected backgrounds

Cut	Data	Sum BGND	QCD	$Z \rightarrow ee$	$Z \rightarrow \tau\tau$
(1) Preselection	33466	$32572.5 \pm 105.9$	$3092.9 \pm 75.7$	$28289.2 \pm 72.7$	$668.5 \pm 6.7$
(2) $Z$ veto	2977	$2952.4 \pm 54.1$	$1037.9 \pm 51.4$	$1564.8 \pm 13.9$	$136.3 \pm 3.9$
(3) significant MET	215	$220.6 \pm 19.0$	$86.6 \pm 17.1$	$15.7 \pm 1.7$	$8.2 \pm 0.9$
(4) 3rd Track OR 2nd tau	3	$3.271^{+0.800}_{-0.800}$	$0.908 \pm 0.712$	$0.588 \pm 0.294$	$0.772 \pm 0.188$
(5) Di-boson veto	1	$0.977^{+0.225}_{-0.189}$	$0.445 \pm 0.174$	$0.0^{+0.120}_{-0.0}$	$0.059 \pm 0.017$
(6) $p_T^{\text{trk}} * E_T$ (further veto QCD, W/Z)	0	$0.582^{+0.112}_{-0.105}$	$0.218 \pm 0.086$	$0.0^{+0.039}_{-0.0}$	$0.050 \pm 0.015$
Cut	$W \rightarrow e\nu$	$W \rightarrow \tau\nu$	$\Upsilon(1s)$	$WW/WZ/ZZ$	$tt$
(1) Preselection	$272.7 \pm 12.8$	$8.5 \pm 1.9$	$192.4 \pm 4.1$	$48.6 \pm 1.3$	$16.3 \pm 0.3$
(2) $Z$ veto	$144.6 \pm 9.1$	$7.3 \pm 1.7$	$49.9 \pm 2.1$	$12.7 \pm 0.9$	$5.3 \pm 0.2$
(3) significant MET	$98.5 \pm 7.8$	$2.5 \pm 1.0$	$0.3 \pm 0.2$	$9.6 \pm 0.9$	$0.7 \pm 0.1$
(4) 3rd Track OR 2nd tau	$0.600 \pm 0.080$	$0.103 \pm 0.042$	$0.0^{+0.009}_{-0.0}$	$0.287 \pm 0.059$	$0.013 \pm 0.008$
(5) Di-boson veto	$0.231 \pm 0.046$	$0.103 \pm 0.042$	$0.0^{+0.002}_{-0.0}$	$0.126 \pm 0.034$	$0.013 \pm 0.008$
(6) $p_T^{\text{trk}} * E_T$ (further veto QCD, W/Z)	$0.154 \pm 0.036$	$0.031 \pm 0.031$	$0.0^{+0.002}_{-0.0}$	$0.116 \pm 0.032$	$0.013 \pm 0.008$

- Expected SUSY signal events at different stages of selections

Cut	C1	D1	D4	E1
$m_{\tilde{\chi}^\pm}$ (GeV)	106	110	110	114
(1) Preselection	$11.20 \pm 0.29$	$9.58 \pm 0.21$	$4.67 \pm 0.09$	$8.73 \pm 0.17$
(2) $Z$ veto	$9.23 \pm 0.25$	$7.57 \pm 0.18$	$3.59 \pm 0.08$	$6.90 \pm 0.15$
(3) Significant MET	$5.90 \pm 0.20$	$4.80 \pm 0.15$	$2.38 \pm 0.07$	$4.46 \pm 0.12$
(4) 3rd Track OR 2nd tau	$1.986 \pm 0.115$	$1.747 \pm 0.111$	$0.973 \pm 0.044$	$1.382 \pm 0.069$
(5) Di-boson veto	$1.271 \pm 0.093$	$1.271 \pm 0.093$	$0.691 \pm 0.037$	$1.059 \pm 0.059$
(6) $p_T^{\text{trk}} * E_T$ (further veto QCD, W/Z)	$1.116 \pm 0.087$	$1.116 \pm 0.087$	$0.634 \pm 0.035$	$0.968 \pm 0.057$

# SUSY: 2<sup>nd</sup> Neutralino and Slepton limits

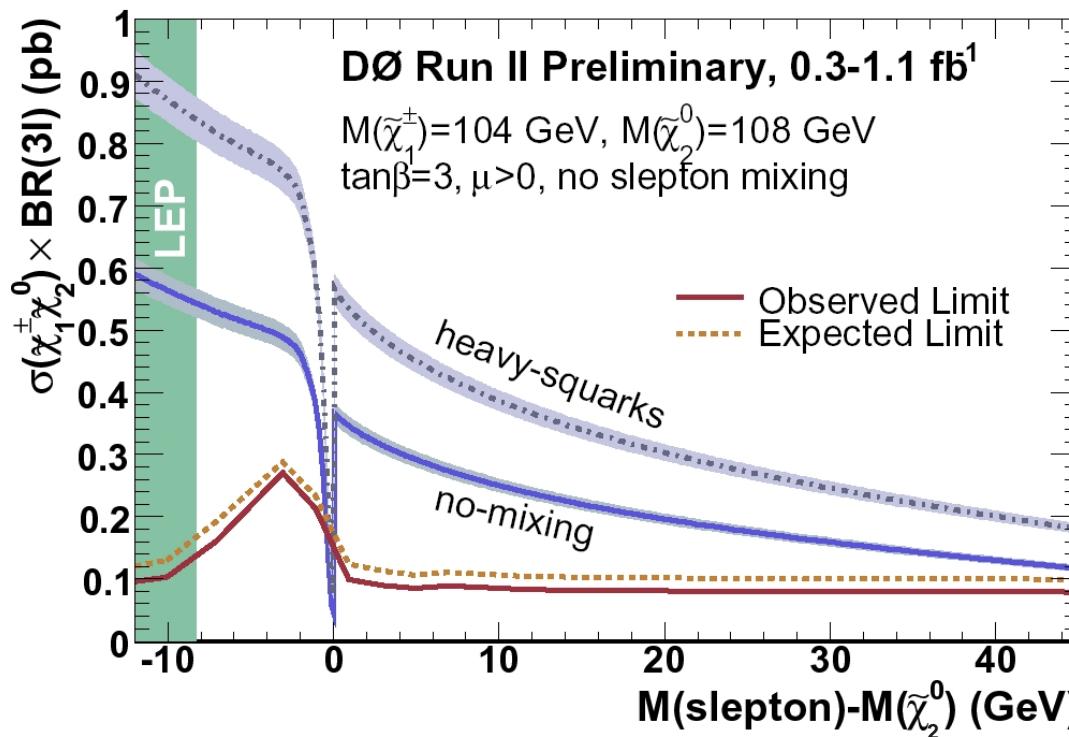
Topology	Data	Expected Background	Signal
eel	0	$0.76 \pm 0.67$	$1.7 \pm 0.1$
e $\mu\ell$	0	$0.31 \pm 0.13$	$1.6 \pm 0.1$
$\mu\mu\ell$	2	$1.75 \pm 0.57$	$1.3 \pm 0.2$
like-sign $\mu\mu$	1	$1.10 \pm 0.40$	$1.3 \pm 0.1$
e $\tau\ell$	0	$0.58 \pm 0.11$	$1.1 \pm 0.1$
$\mu\tau\ell$	1	$0.72 \pm 0.26$	$0.8 \pm 0.1$

Selections based on Signal:

$$\tan\beta = 3, \mu > 0$$

$$m_{\tilde{\chi}^\pm} = 110 \text{ GeV}, m_{\tilde{\chi}_0^0} = 55 \text{ GeV}$$

- Data consistent with backgrounds  $\Rightarrow$  upper limits on  $\sigma(\tilde{\chi}_1^\pm \tilde{\chi}_2^0) \times \text{BR}(3\ell)$



Drop in BR(3l) at  $m_{\tilde{\ell}} \sim m_{\tilde{\chi}_2^0}$   
 $\Rightarrow$  phase-space for 2-body decays into real sleptons is minimal